# DISCRIMINATING ELECTROMAGNETIC AND HADRONIC SHOWERS IN THE MINERvA DETECTOR

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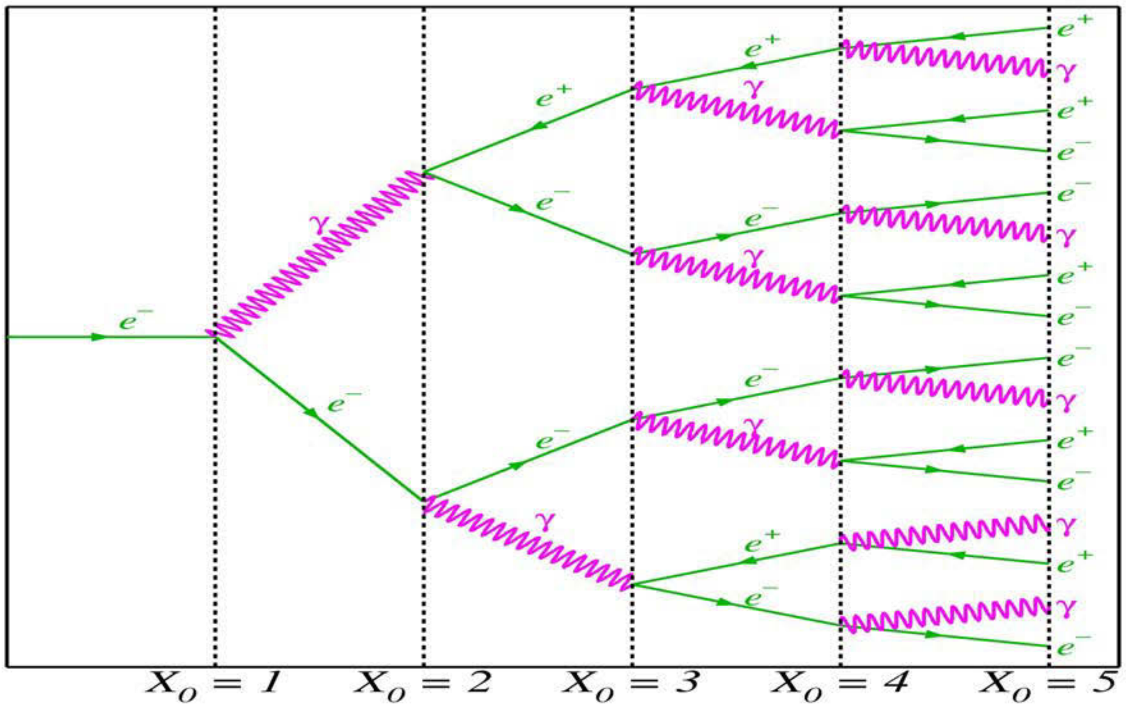
# What are particle showers?




http://www-zeus.physik.uni-bonn.de/~brock/feynman/vtp_ws0506

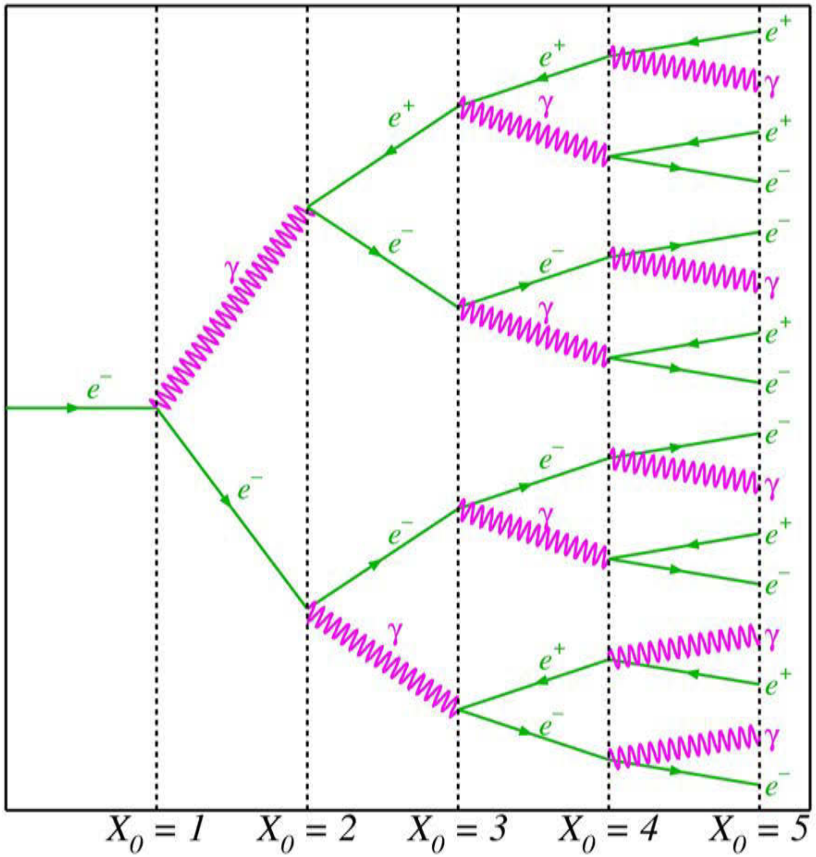
- Showers are often produced when particles interact with matter

# Electromagnetic and hadronic showers

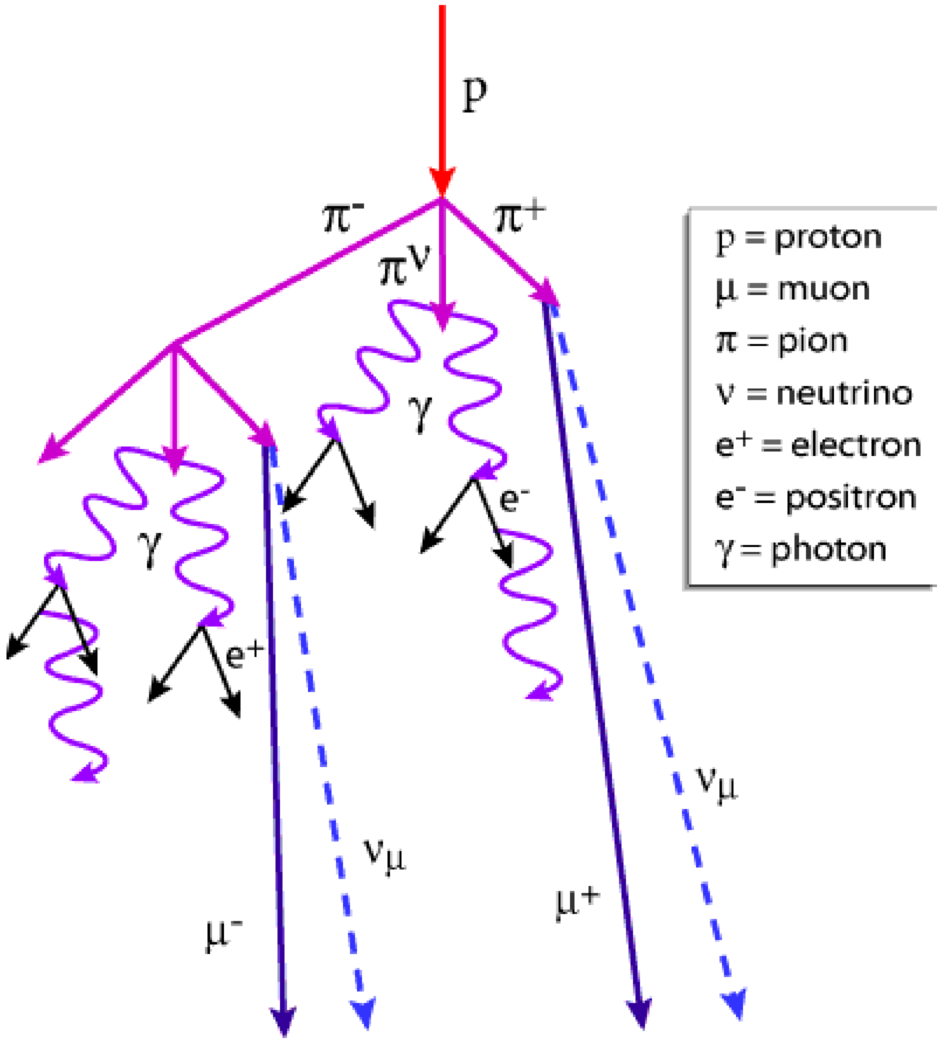
- EM showers are produced by electrons, positrons and photons
- Hadronic showers are produced by hadrons such as $\pi^+$ and $\pi^-$
- Distinguishing them helps us determine what particles are produced in an interaction

# Electromagnetic showers

- When electrons interact with matter they produce photons, which then pair produce electrons and positrons
- The result is a cascade of particles – a particle shower

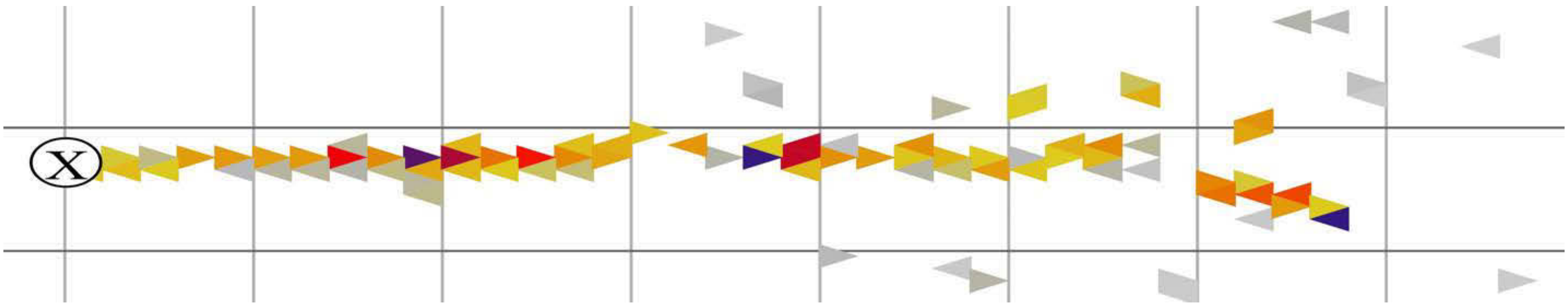


# Hadronic showers

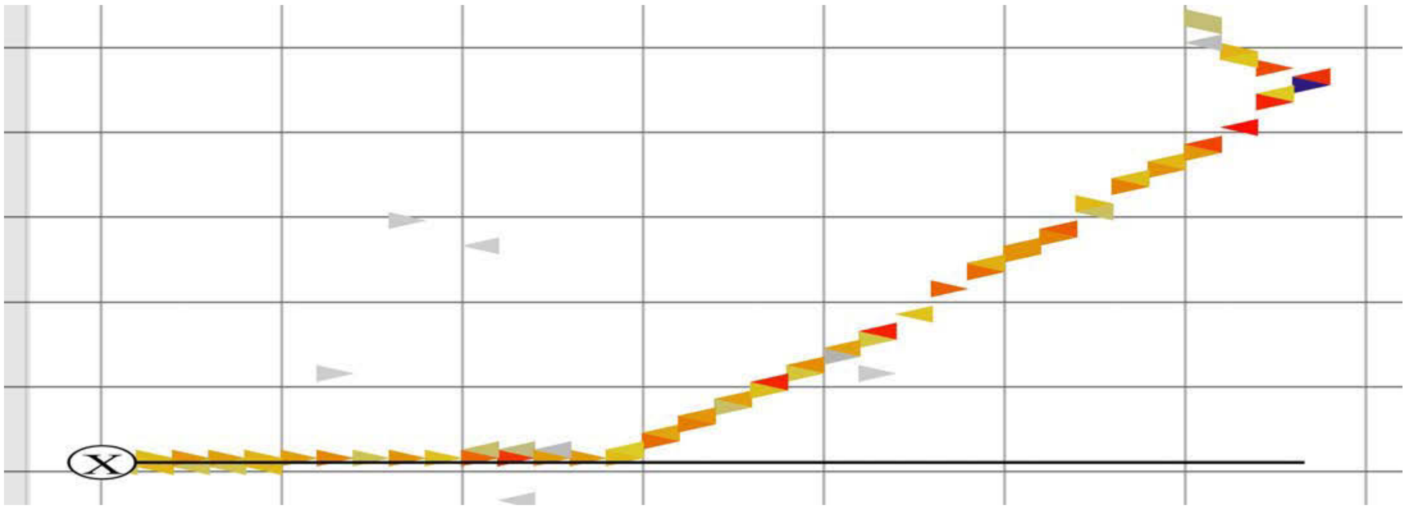



- Hadronic showers are more chaotic – involving the production of both hadrons and leptons. The results may be a shower which also has parts which are electromagnetic showers

# Showers




Em shower





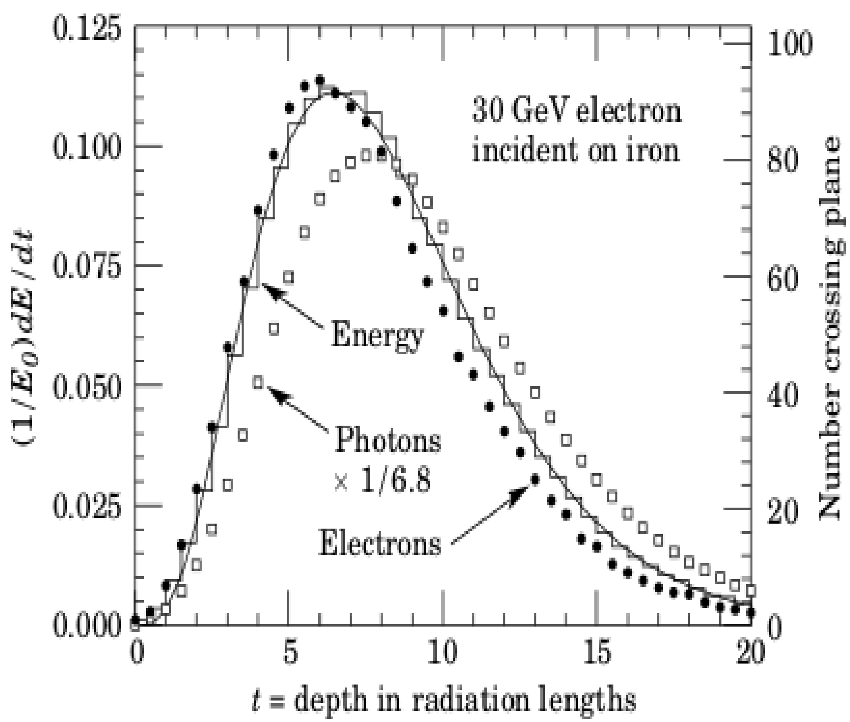

Piplus shower

# Electromagnetic showers

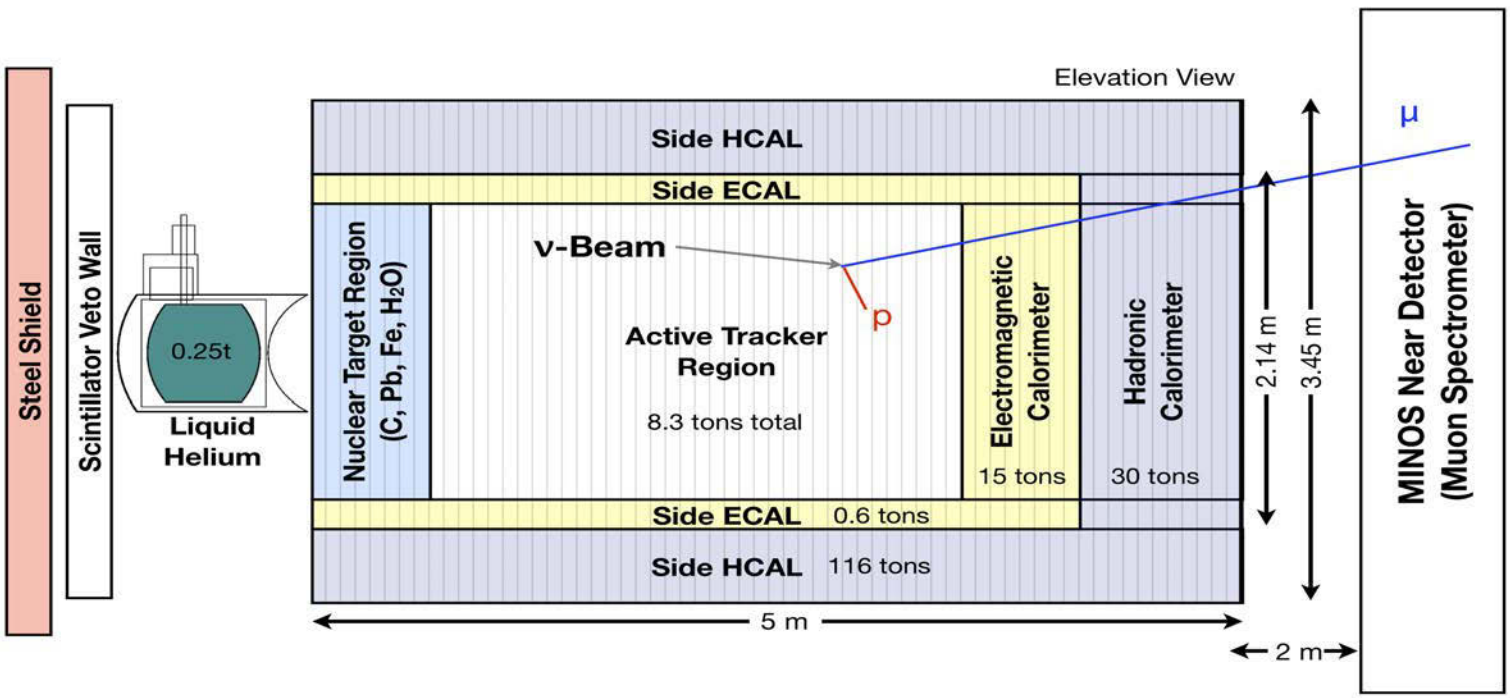
- We expect electrons to deposit energy in a well-defined pattern, given by the function:

$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

- Hadronic showers are not similarly well-defined
- (A radiation length is the distance over which an electron in matter's energy is reduced by 1/e)



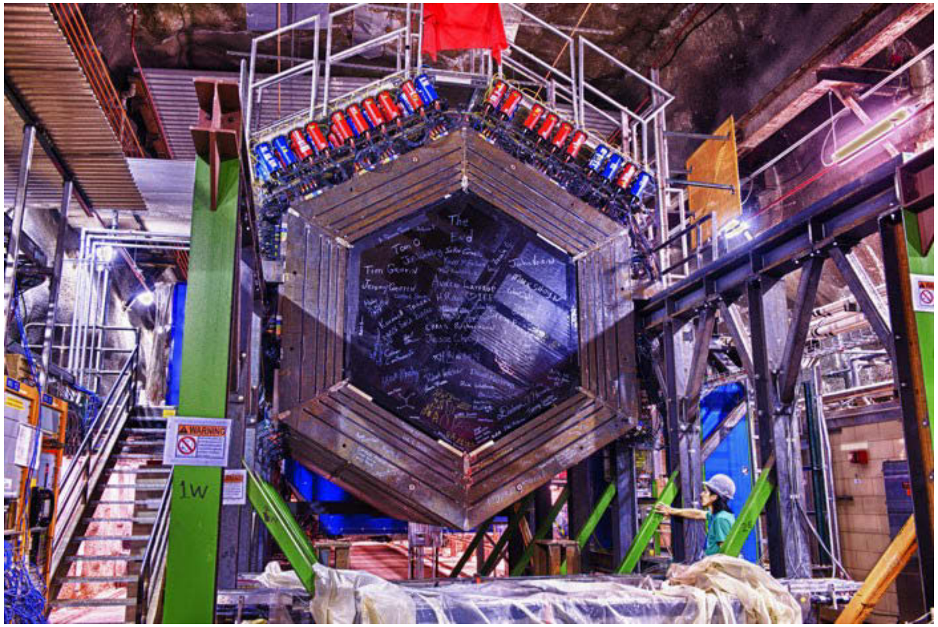
# MINERvA




- The purpose of MINERvA is to detect neutrinos
- It consists of several subdetectors. The tracker region is made of polystyrene scintillator, and the electromagnetic calorimeter is made of polystyrene interspersed with layers of lead
- I focus on these two subdetectors in my research

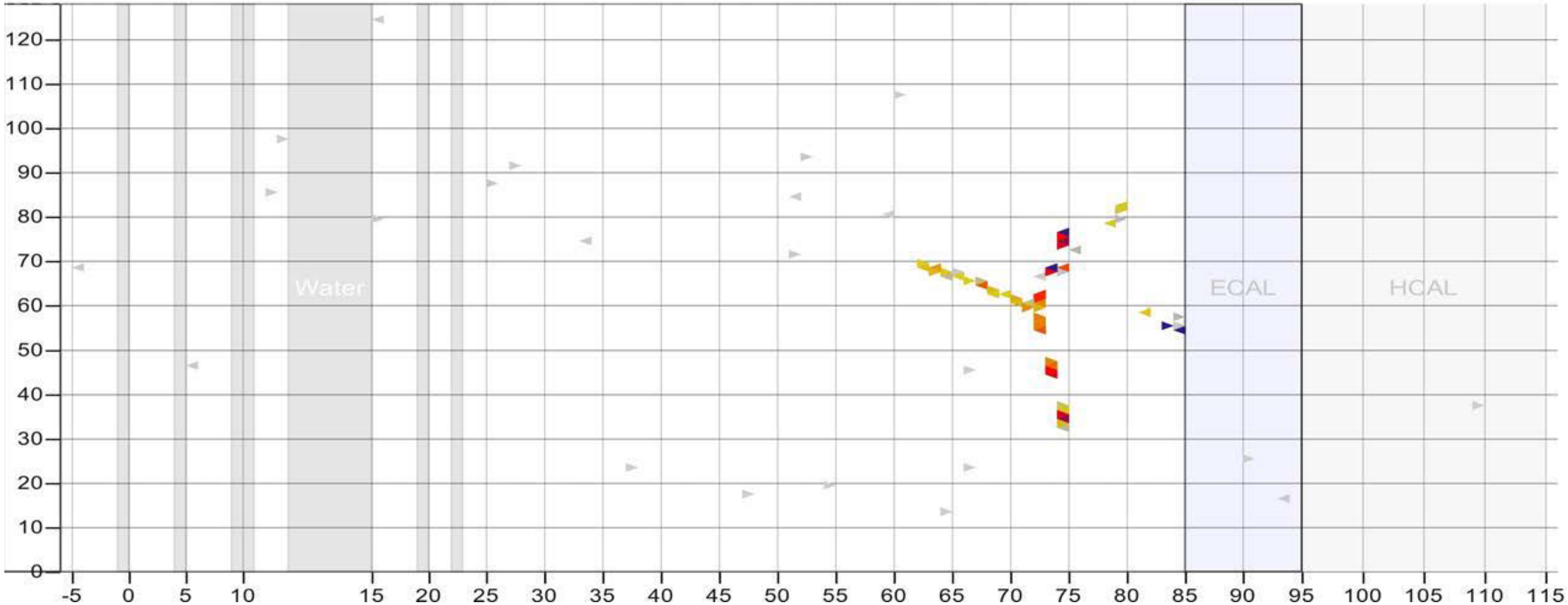
# MINERvA

- The MINERvA tracker consists of planes of scintillator which are each lined with strips stretching across the plane
- The strips are oriented in three different directions in each plane – X,U,V – each at 60 degrees to each other



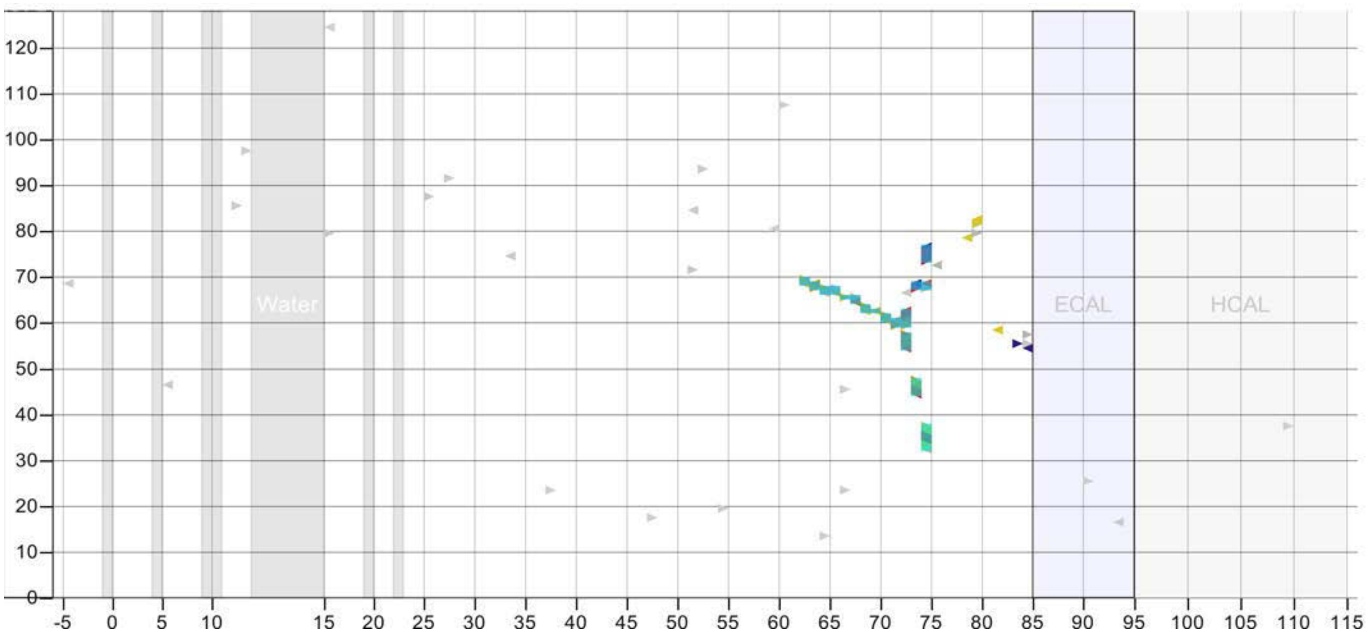
# MINERvA

- The results is three planes each giving 2 dimensional information about energy deposition



# Blobs

- I used IsolatedIDBlobCreator to group the clusters in an event into topologically connected groups called "blobs"



# Distinguishing types of showers

- In this project, I focused on examining how $e^-$ showers might be distinguished from $\pi^+$ showers in the MINERvA detector.

- Only Monte Carlo data was used.

- Only clusters which formed part of blobs were used in the analysis of shower energy. A shower was considered to be a combination of all blobs in an event. Furthermore, any showers reaching the ecal were discarded.

- Several parameters were devised in an attempt to distinguish these types of showers:
  - Longitudinal energy deposition profiles were examined, to see if energy is deposited differently between both types of showers.
  - The energy deposited at the beginning and end of showers was examined.
  - The energy deposited within a cone and cylinder surrounding the shower was examined, as we would expect hadronic showers to have a greater transverse extent.

# Initial set-up

- Initially, 30,000 events of $e^-$ and $\pi^+$ were generated for energies of 100 MeV, 150 MeV, 200 MeV ... 1000 MeV

- They were all generated at zero theta angle and zero phi angle

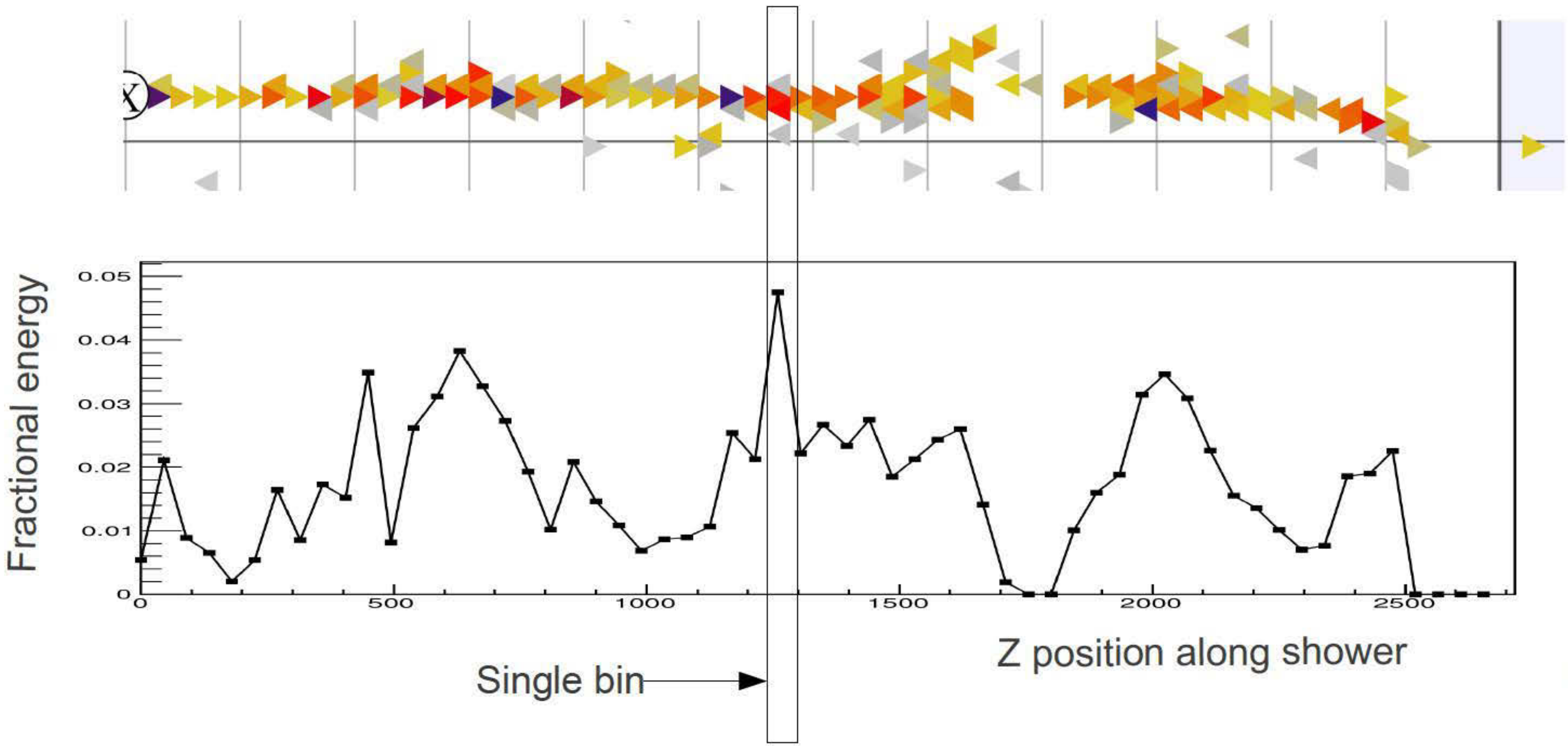
- They were all generated at a starting position at module 25, z=5900.83mm

- They were reconstructed with IsolatedIDBlobCreator

# Energy Profiles

- To get an idea of the energy deposition by $e^-$ at different energies, an average energy deposition template was generated for each energy from 100 MeV to 1 GeV in increments of 50 MeV

**Example of the contribution to an energy profile in a single view**

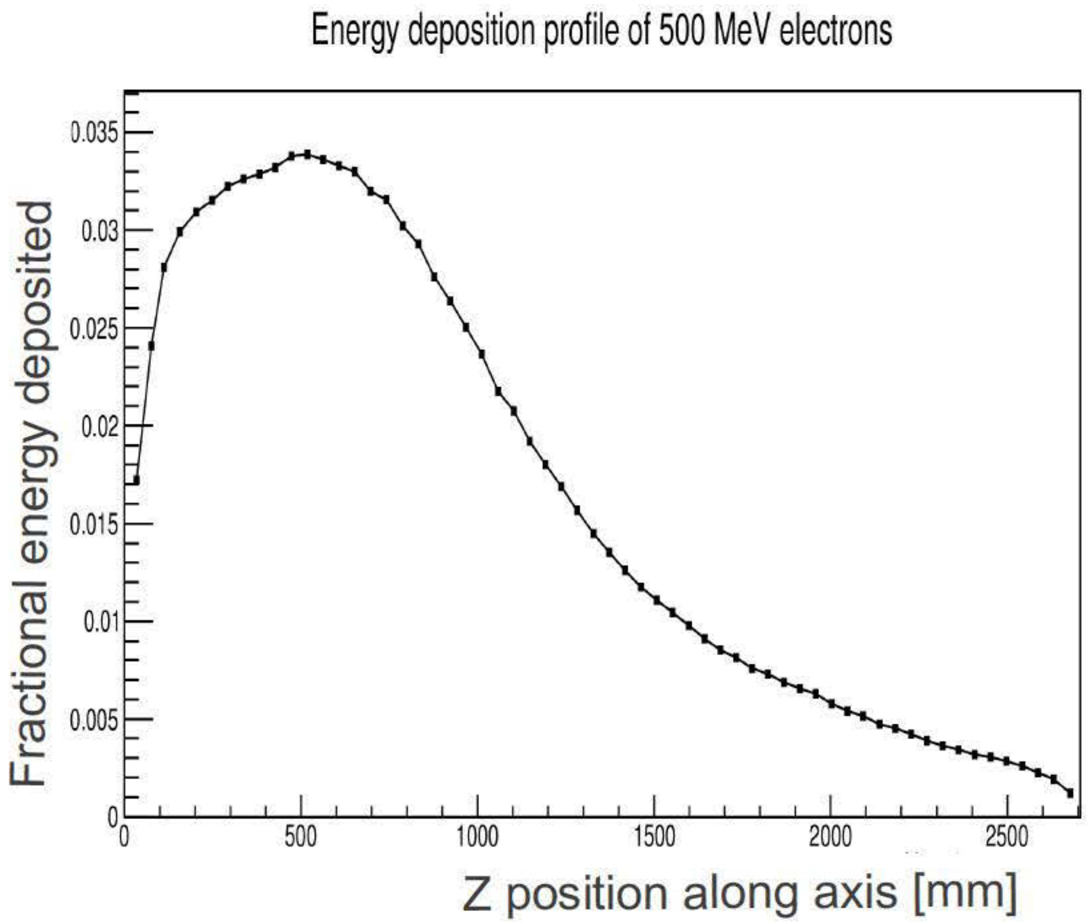


# Energy profiles

- Different templates were produced because we expected the profiles to have different lengths for different energies

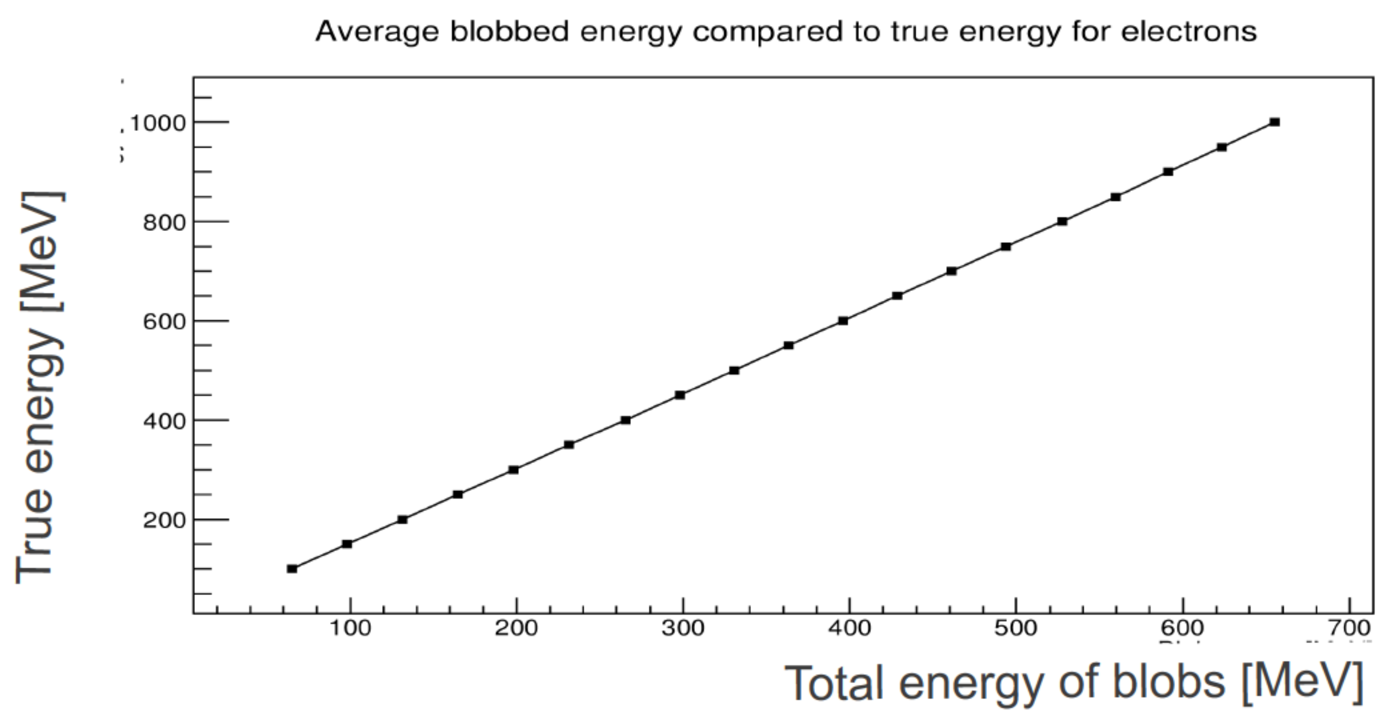
- A series of bins were defined along the axis of the shower, taken to be the z-axis, and the energies of all blob clusters found in a bin in an entry were added up to give a value for that bin in that entry.

- For each energy, a template was produced – i.e. the average longitudinal energy deposition that we would expect from an electron of a certain energy



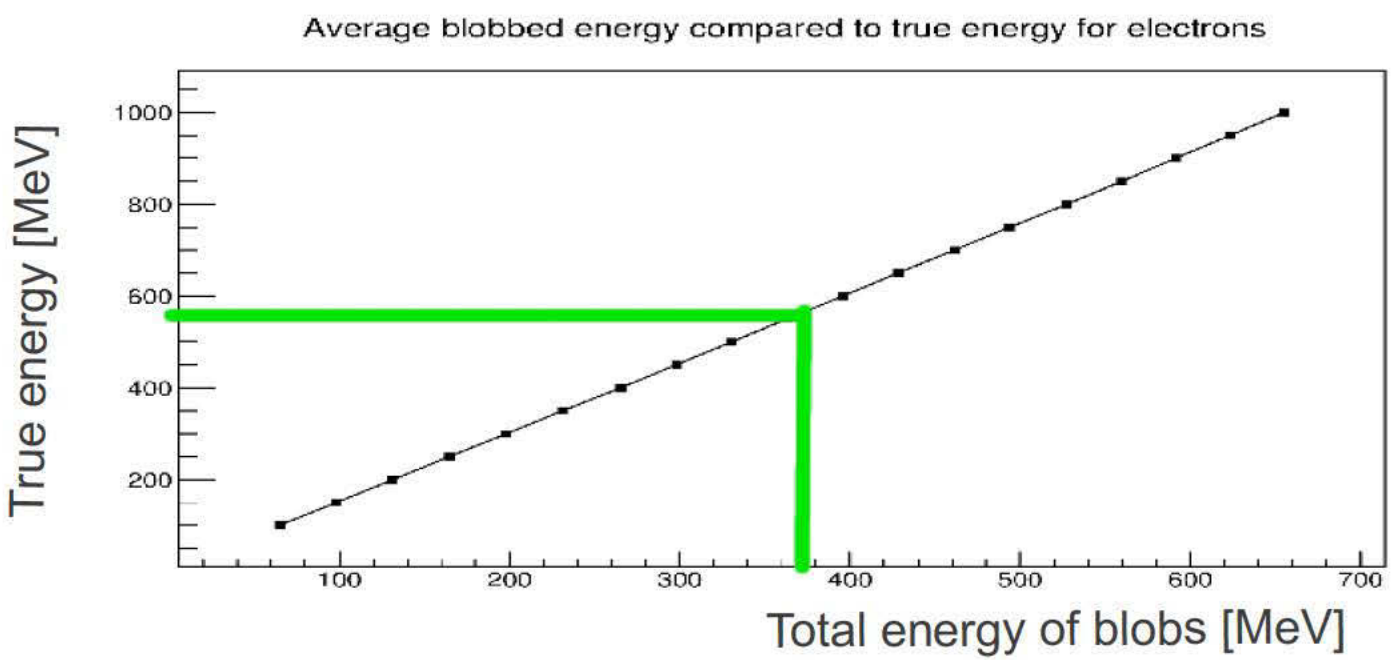
# Comparison of data to templates

- Templates are based on average energy deposition, but event-by-event there will be deviations. There will a range of reconstructed energies for any given true energy.
- The average shower energy – the sum of the blob energies – was compared to true energy for each generated sample



# Comparison of data to templates

- On average, blobs contained about 65% of the total true energy, and this was quite consistent across the range of energies
- For any single event, then, the appropriate template for comparison was chosen by scaling up the observed shower energy to an assumed true energy

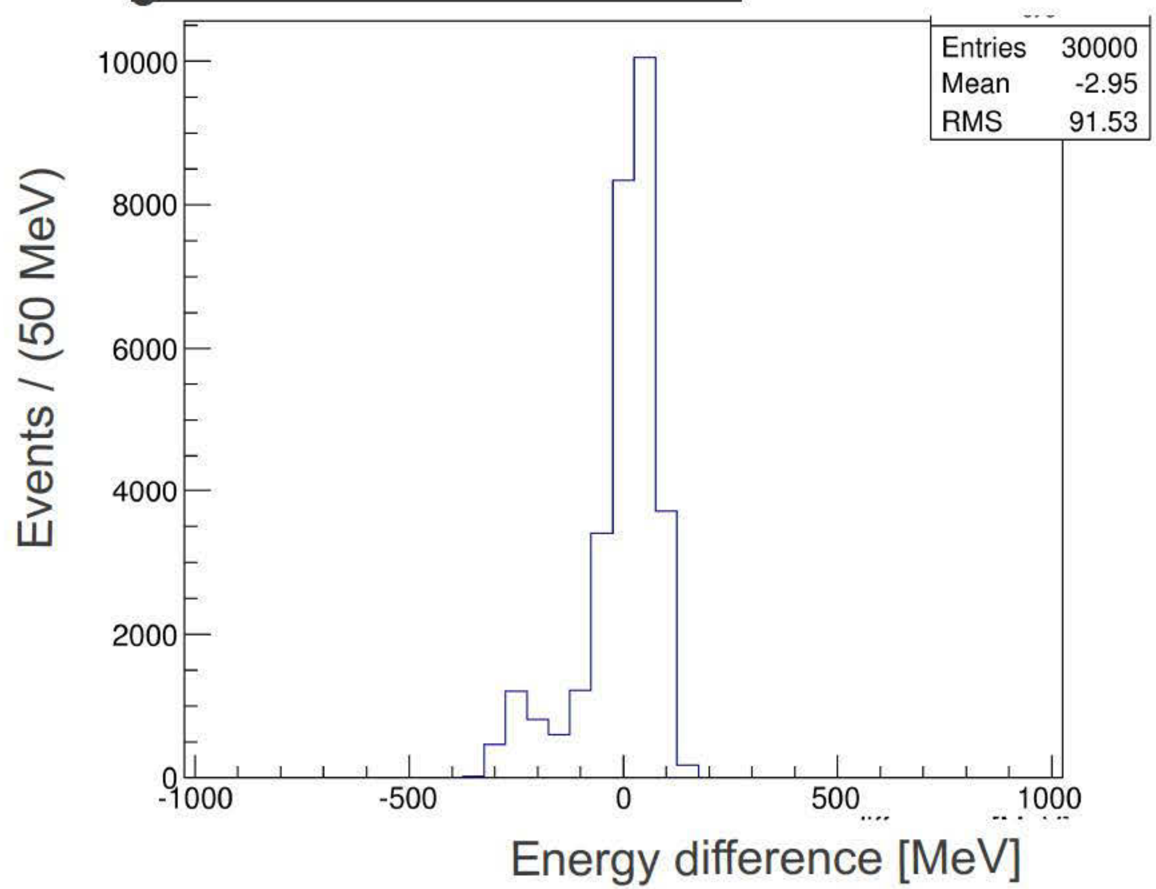


# Comparison of data to templates

- The validity of this approach was investigated by plotting the energy identification for any given true energy sample

- For example, for 500 MeV electrons, most electrons were identified as being reasonably close to 500 MeV – such that either the 500 MeV template or the similar adjacent ones would likely be used for comparison

Difference between true energy and energy guess for 500 MeV electrons



# Comparison of data to templates

- Many individual Monte Carlo generated entries were compared to the templates by getting a chi-square value:

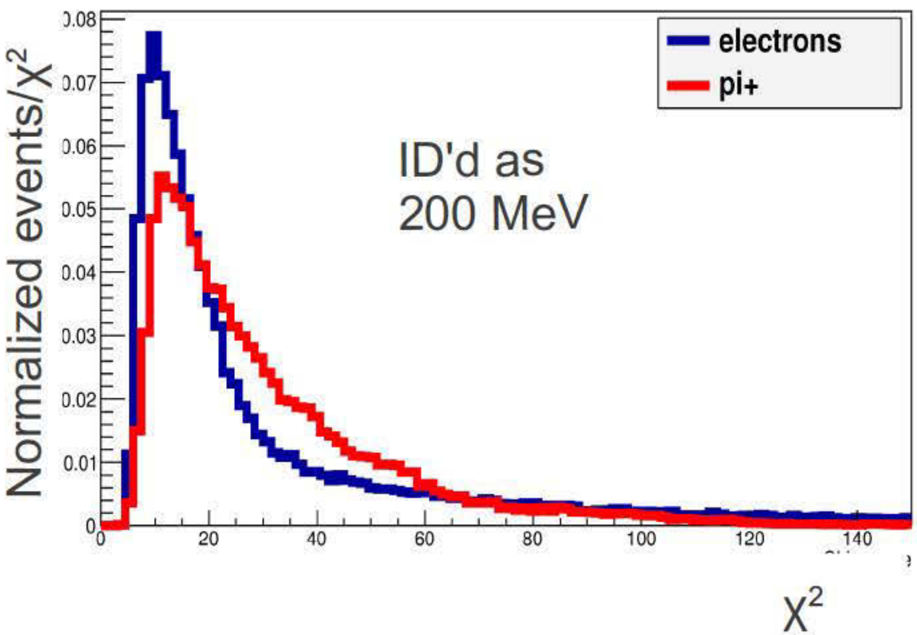
$$\chi^2 = \sum_{i=1}^{N} \left( \frac{x - x_i}{rms_i} \right)^2$$

- N is the number of individual entries used to make the template, i is

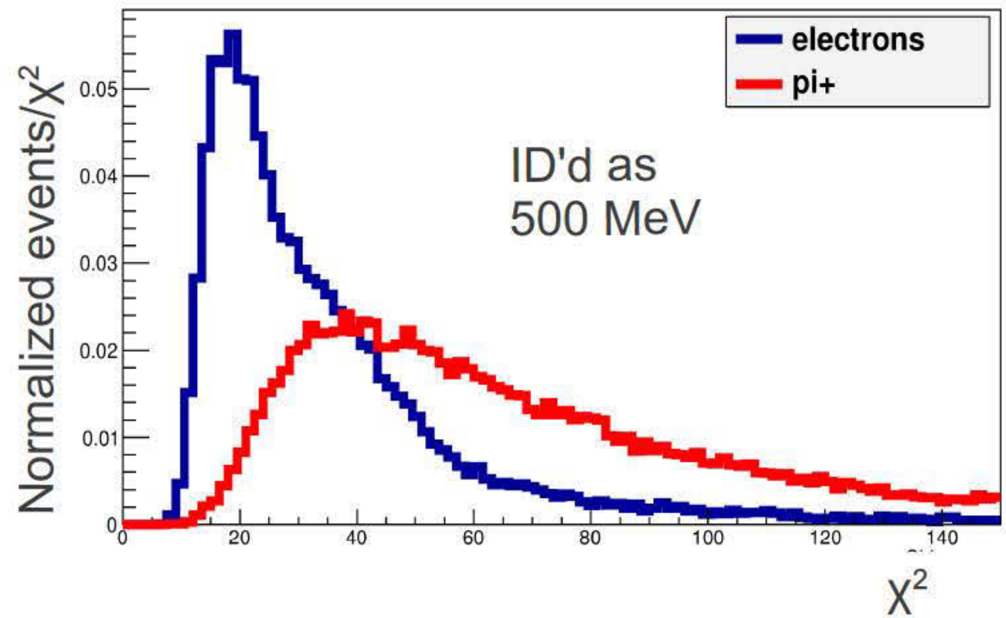
  an individual entry, x is the energy in a bin, and rms is the root mean square of the total energy contributions *across all events* for each bin of the template. An rms was therefore generated for each bin, enabling direct comparison with the same bins of energy profiles
- The chi-squares for all electrons identified with a certain template were plotted together to give a chi-square graph associated with each template

# Chi-squares compared to templates

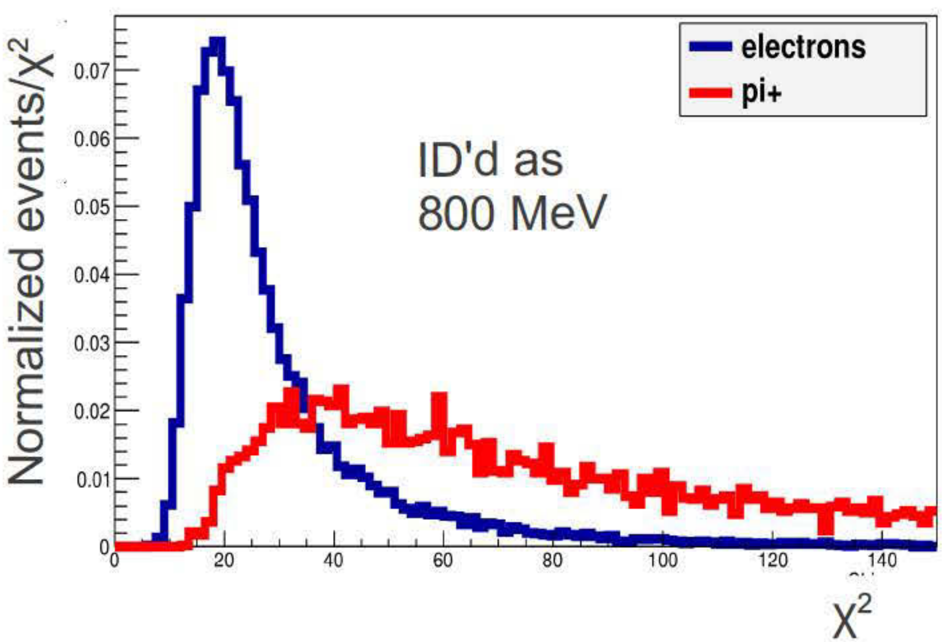
Chisquares compared to templates for particles identified as 200 MeV



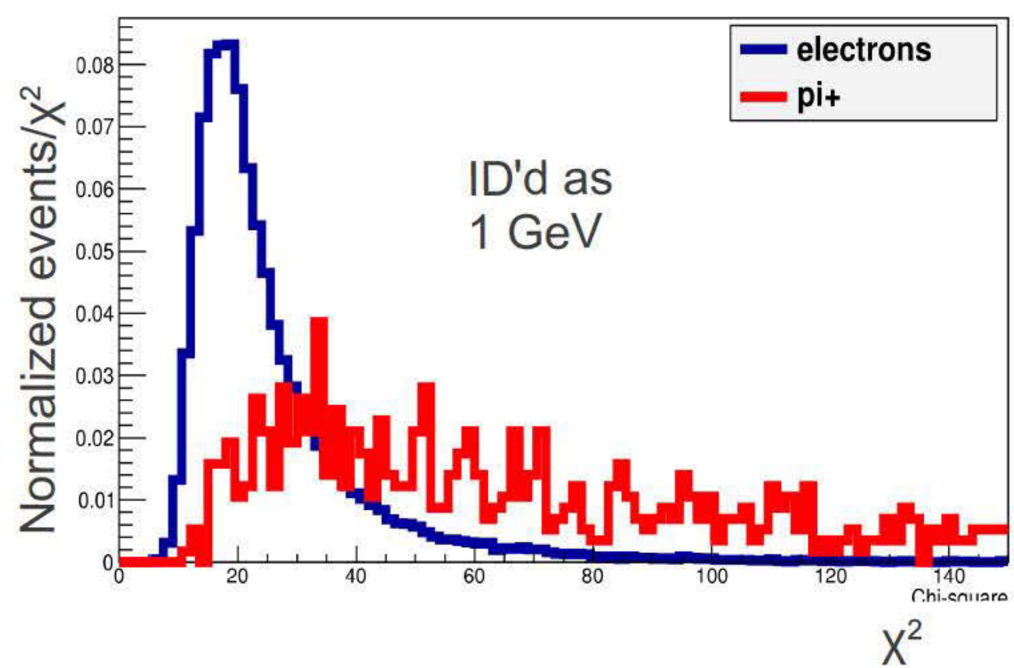

Chisquares compared to templates for particles identified as 500 MeV




Chisquares compared to templates for particles identified as 800 MeV




Chisquares compared to templates for particles identified as 1000 MeV



# Other methods of distinguishing

- There is clearly some separation between $e^-$ showers and $\pi^+$ showers. However there is considerable overlap, suggesting other methods are necessary to better distinguish them

- I looked into several other features for distinguishing showers:
  - The energy deposition in the first and last portions of the shower
  - The amount of energy deposited within a cylinder or a cone surrounding the shower
  - The degree to which a shower is isolated from other events in its vicinity

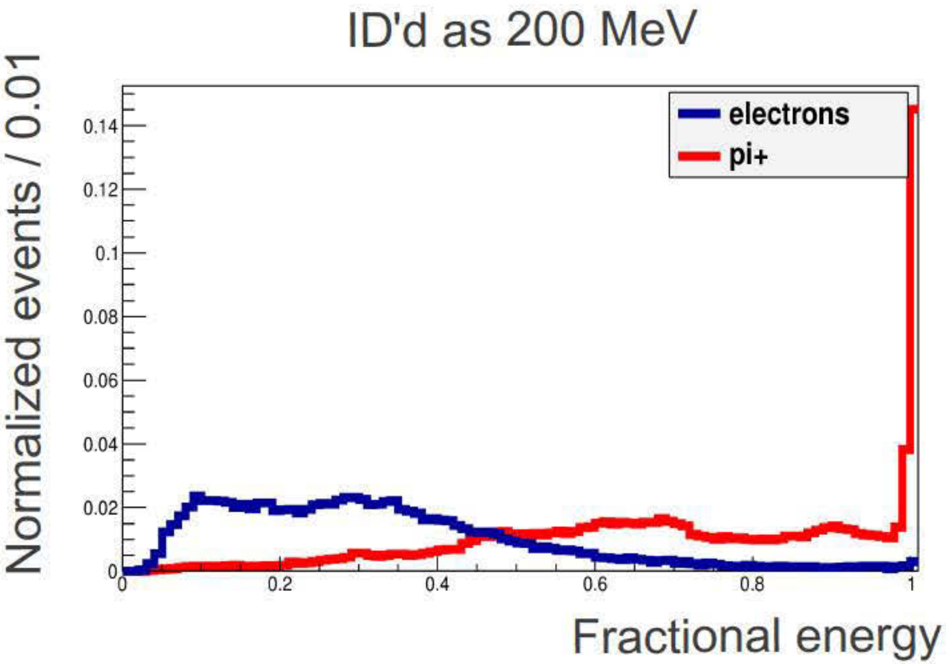
# Energy deposition at end of shower

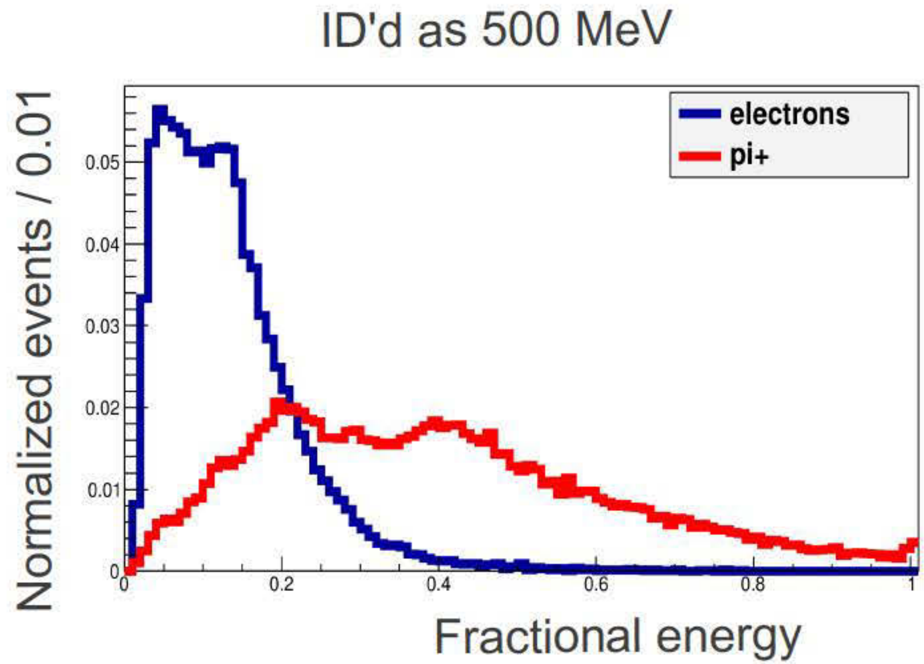
- For $e^-$ most energy tends to be deposited in the first portion of the shower, as can be seen from the energy profiles

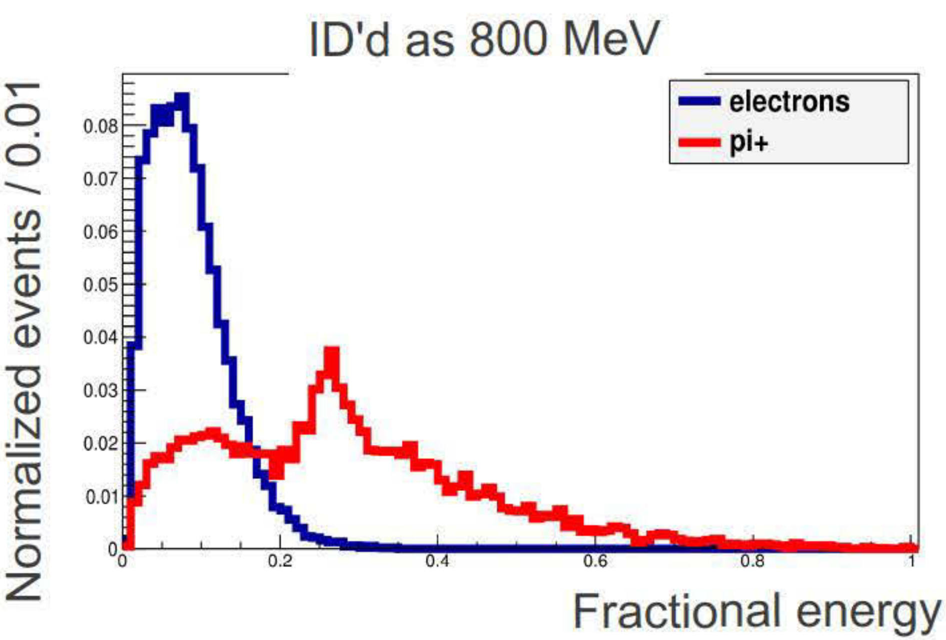
- For $\pi^+$ there is more variation in energy deposition, and it is often the case that a lot of energy is deposited towards the end

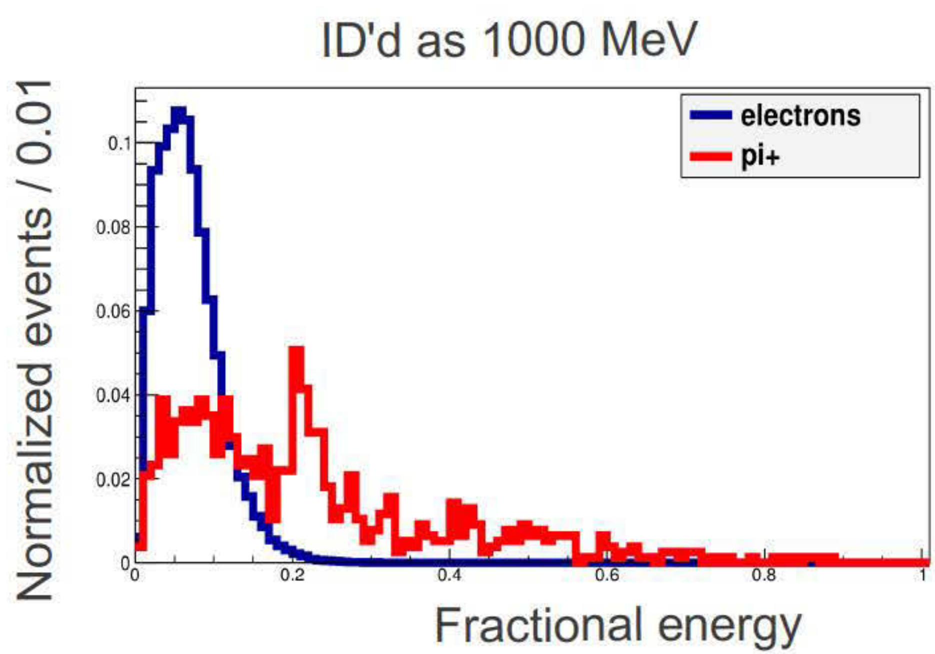
- For our set-up, the energy deposition in the last 200mm of the shower was examined (corresponding to about five modules in MINERvA)

# Energy deposition in last 200mm of shower



# Energy deposition within a “cylinder”

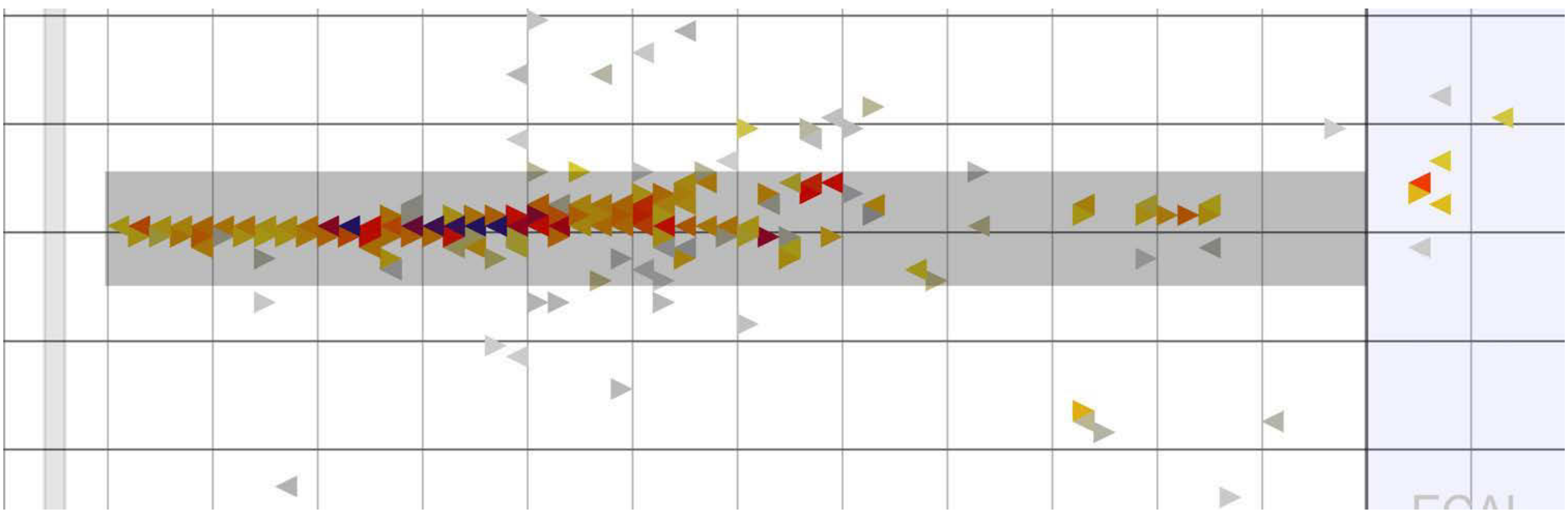
- The Moliere radius is defined as the radius surrounding a shower's axis within which 90% of the shower's energy is deposited

- This is a common way of distinguishing electromagnetic from hadronic showers, as electromagnetic showers tend to have a smaller average transverse extent than hadronic showers

- Three-dimensional information about energy deposits was not available for this analysis, and since we were dealing with blobs, so the concept of Moliere radius could not directly be applied – but a criterion based upon the general idea was developed

# Energy deposition within a “cylinder”

- In each plane, the vertical location of the z-axis was estimated by taking a weighted fit of the clusters within the first 5 modules of the start of the shower
- A “cylinder” was defined by choosing a common vertical distance above and below the axis line in each of the X,U and V views



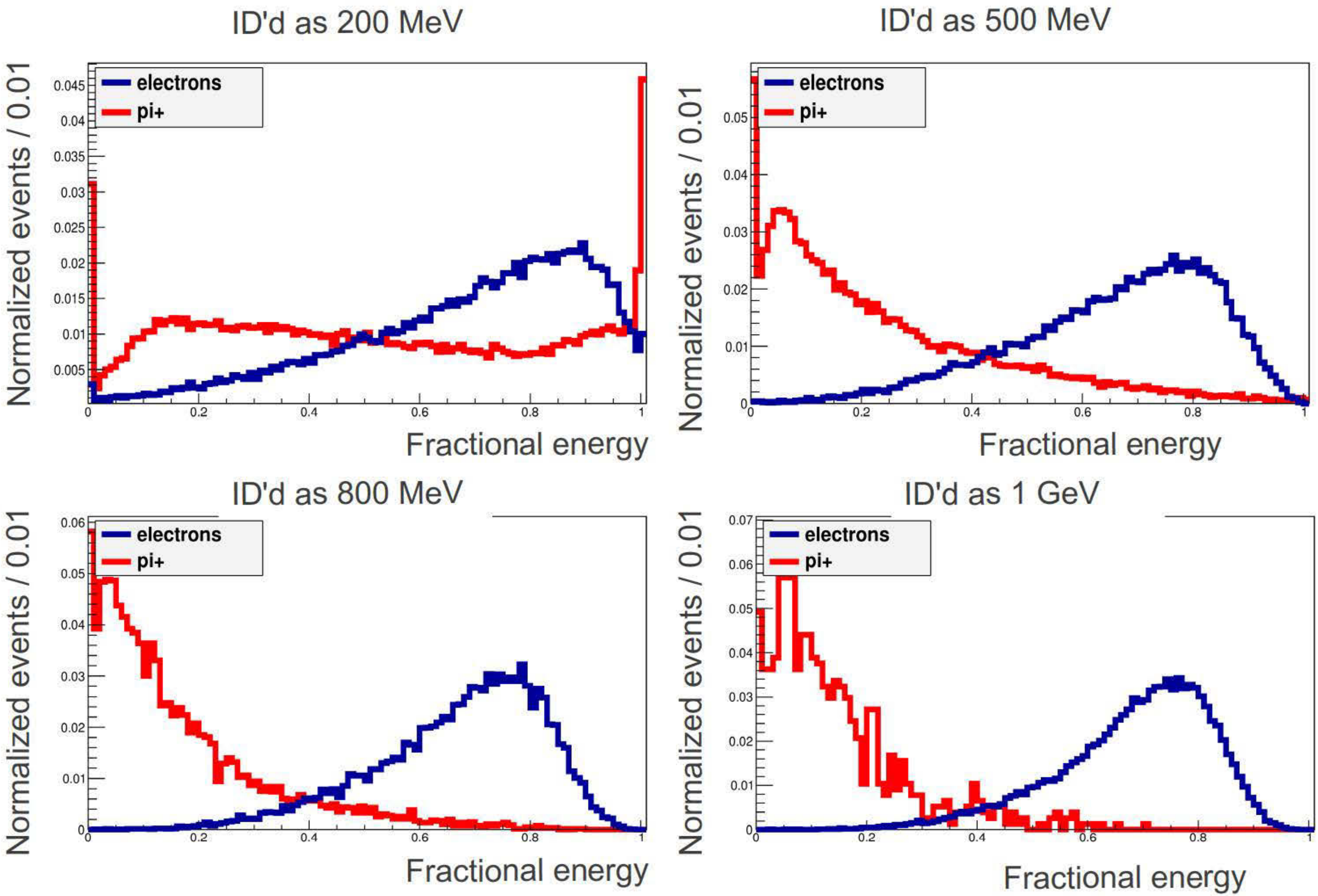
# Energy deposition within a “cylinder”

- It's not a real 3D cylinder, but a combination of three 2D “roads” or “strips”

- The fraction of the total blob energy inside the cylinder was calculated for each generated energy

- Various cylinder radii were looked at, and 20mm was observed to give a good separation between electron and piplus showers

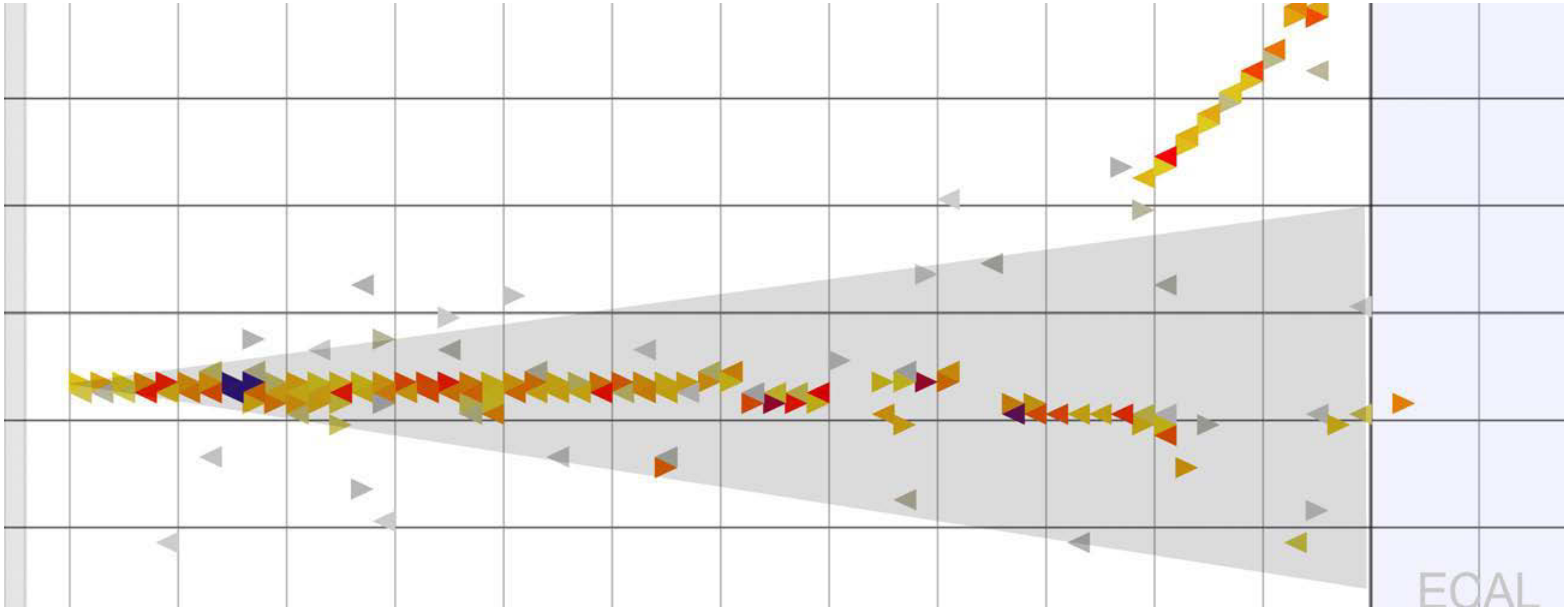
# Energy deposition within a “cylinder” of radius 20mm



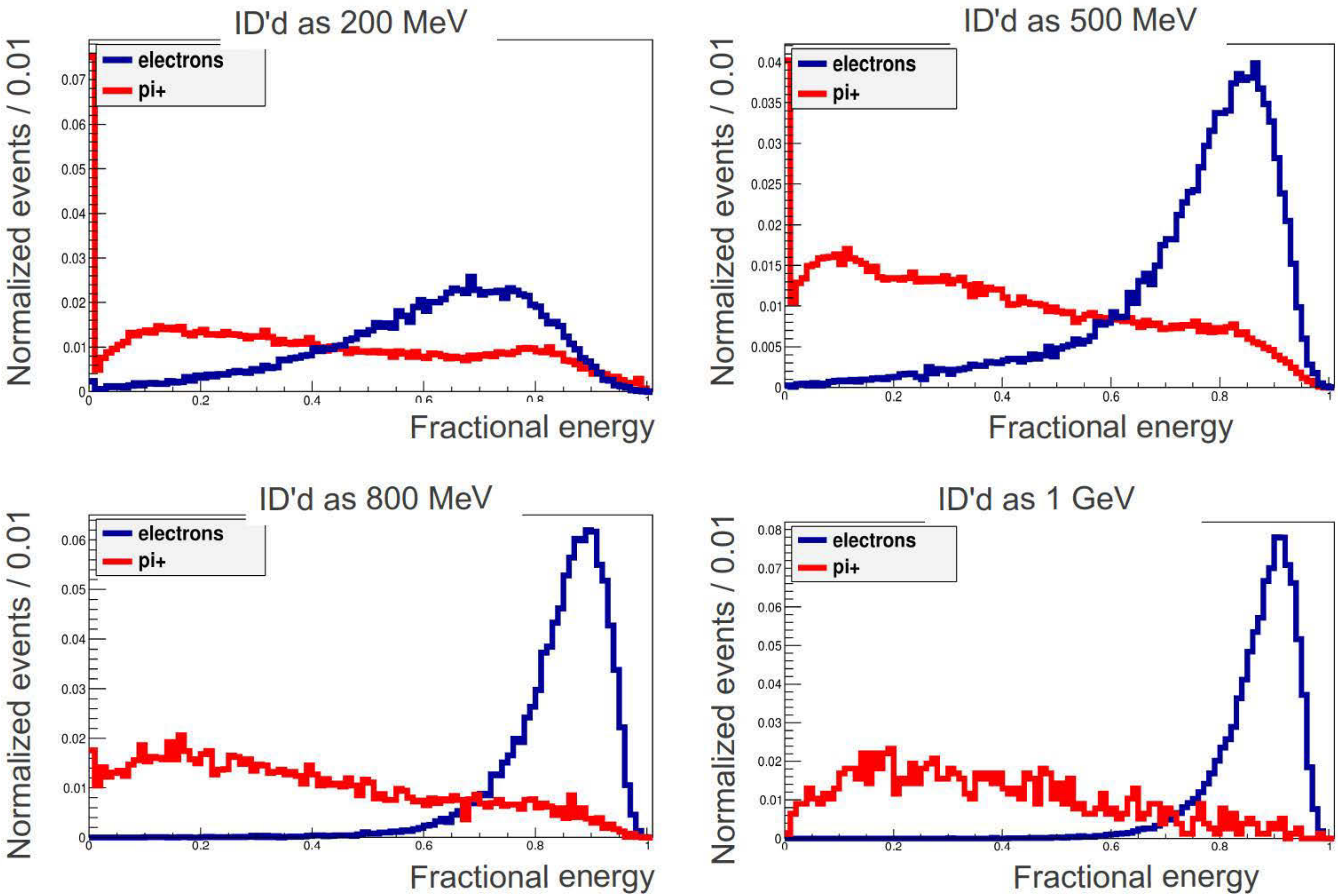
# Energy deposition within a “cone”

- Similar to the “cylinder”, a “cone” whose axis passes through the starting point of the shower would be expected to separate narrow from wide showers.

- But in the same way that a true cylinder could not be used, neither could a true cone.



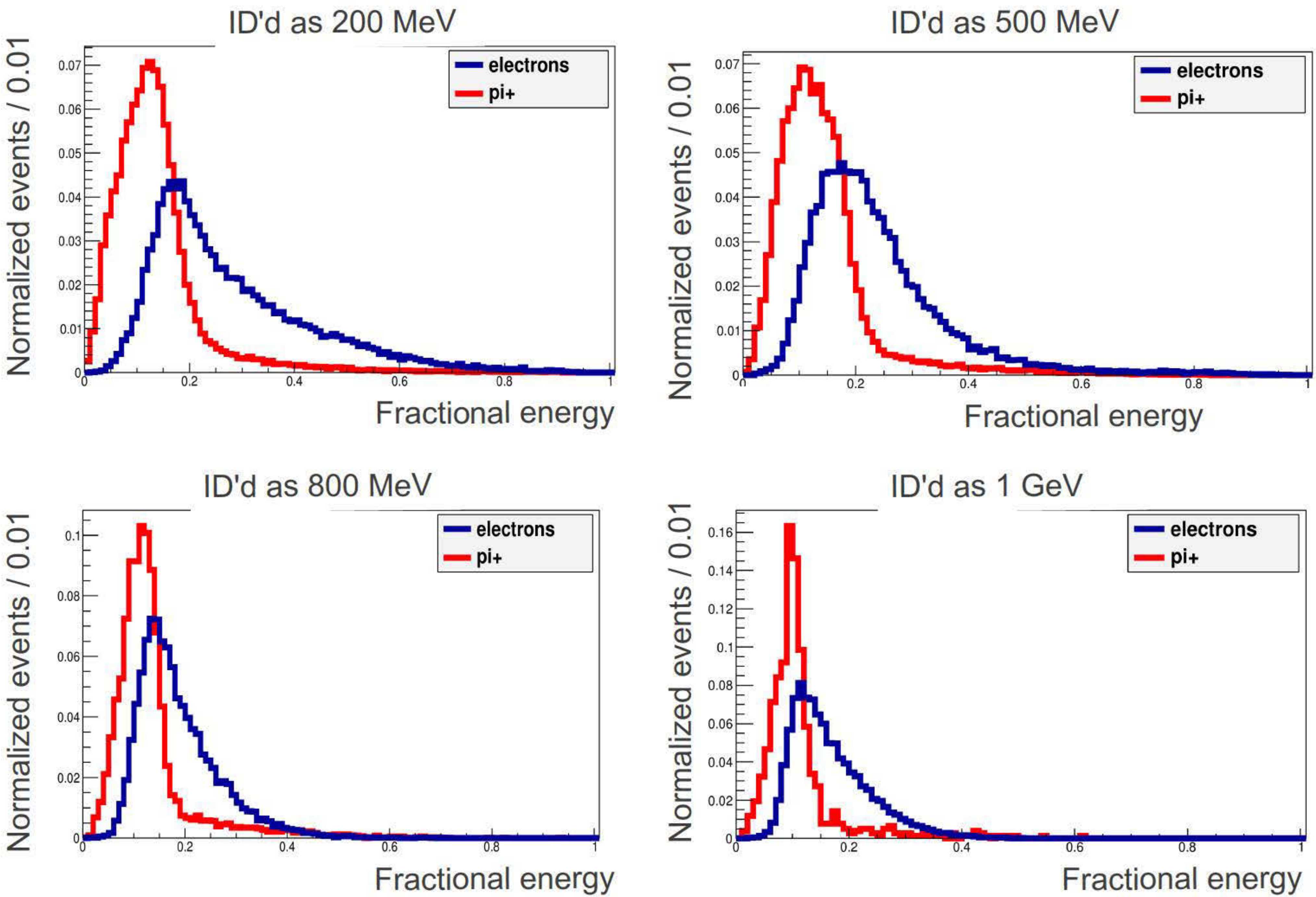
# Energy deposition within a “cone” of angle 0.05 radians



# Energy at the start of the shower

- As there's a noticeable difference in the energy deposition at the end of the shower, we might also expect a difference at the start
- The end of the shower was defined as the position of the last blob cluster, and the energy deposited within the first 20 percent of the shower was plotted
- Again, as we would expect, more energy on average is deposited at the start of the shower by $e^-$ than by $\pi^+$
- This is likely due to the importance of radiative effects in the interaction of even relatively low energy $e^-$ with matter

# Fractional energy in the first 20% of the shower length



# Isolation parameter

- For cases where several showers develop due to more complicated interactions, it may be useful to consider how isolated a shower is

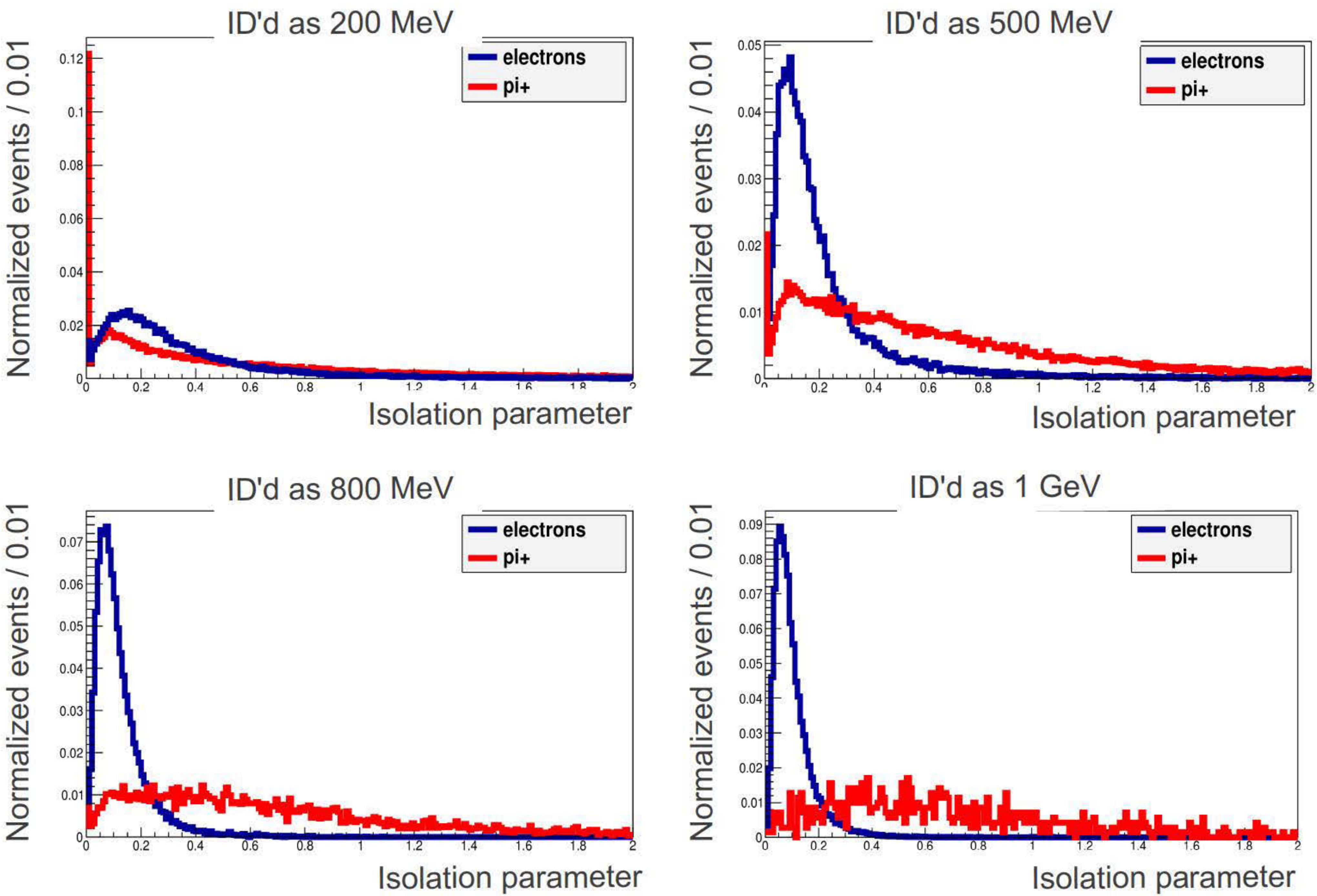
- For this purpose we may define an isolation parameter as:

$$p_{iso} = \frac{E(2\alpha) - E(\alpha)}{E(\alpha)}$$

  where α is the angle of any "cone" as defined previously, and E is the energy within such a cone

- The lower the value of this parameter, the more isolated is a particle shower

# Isolation paramater with α = 0.05 radians



# Combining the results

- In order to get a cleaner separation between both types of shower, it would be useful to combine the results
- Now that we know several effective discriminants, we can combine them in a neural net
- For this purpose, I used the ROOT class TMultiLayerPerceptron
- I made a neural net for each energy step from 100 MeV to 1 GeV in increments of 50 MeV

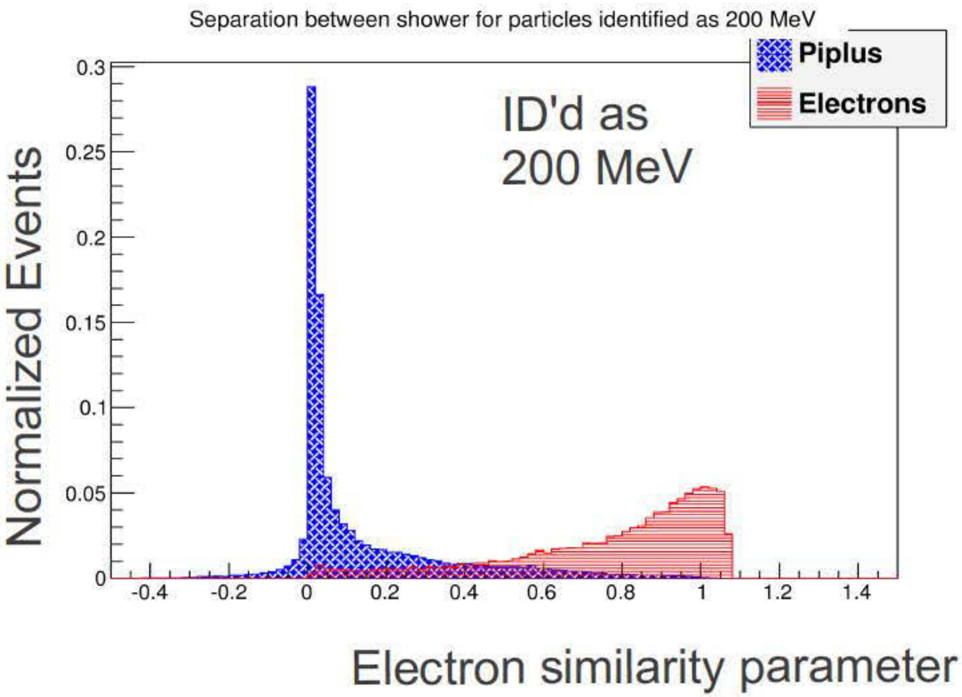
# Combining the results

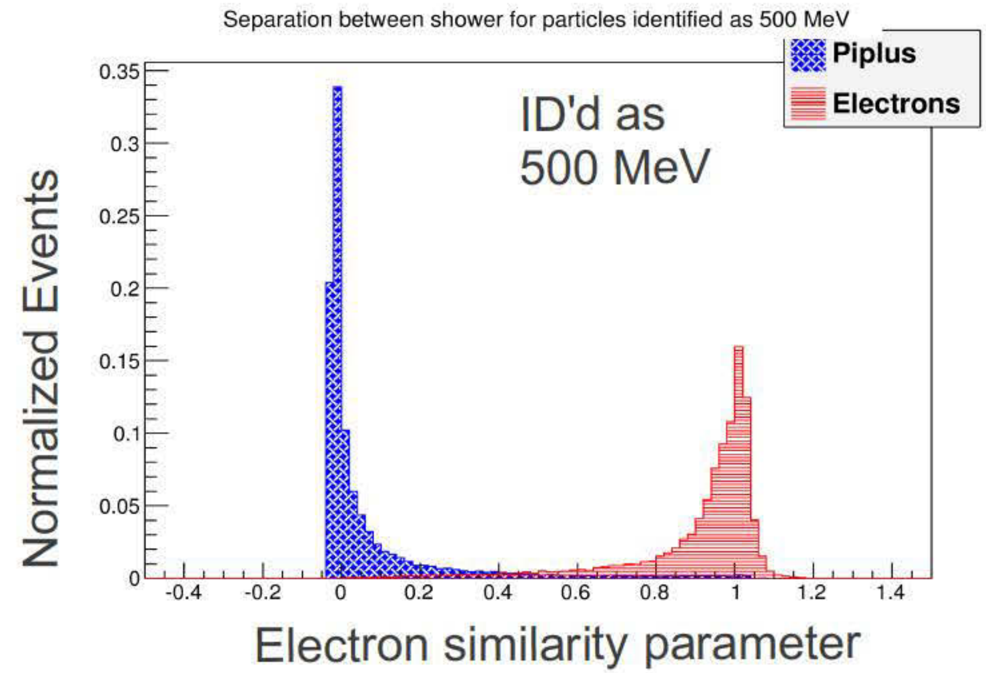
- The parameters used were:
  - Fraction of energy within a “cylinder” of radius 20mm
  - Fraction of energy within a “cone” of angle 0.05 radians
  - Fraction of energy in the first 20 percent of the shower
  - Fraction of energy in the last 5 modules of the shower
  - Chi-square relative to the templates

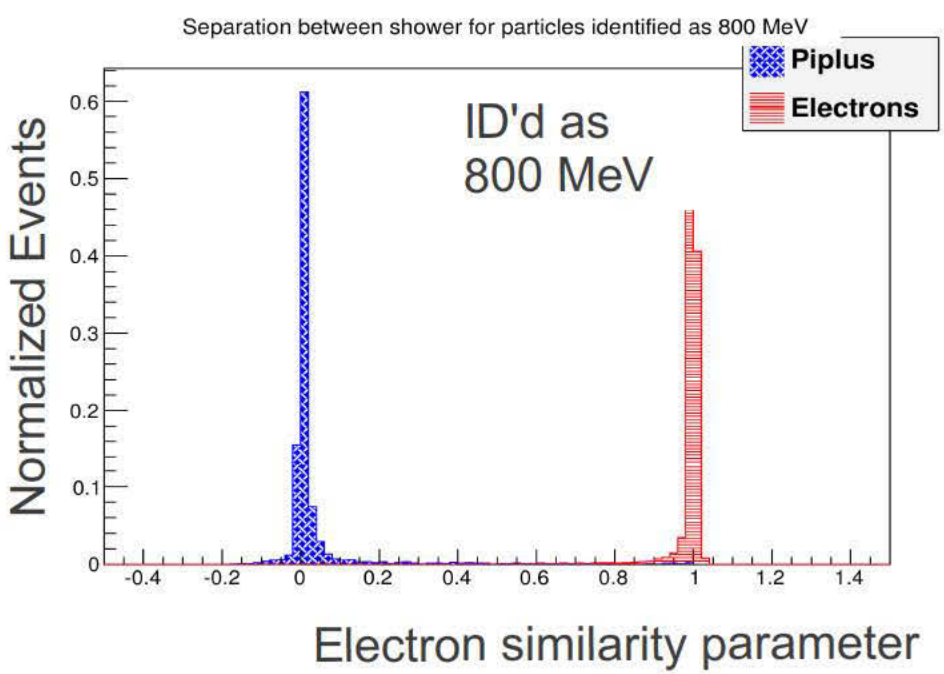
- I used three layers in the perceptron: the input layer, the output layer, and one hidden layer with seven neurons

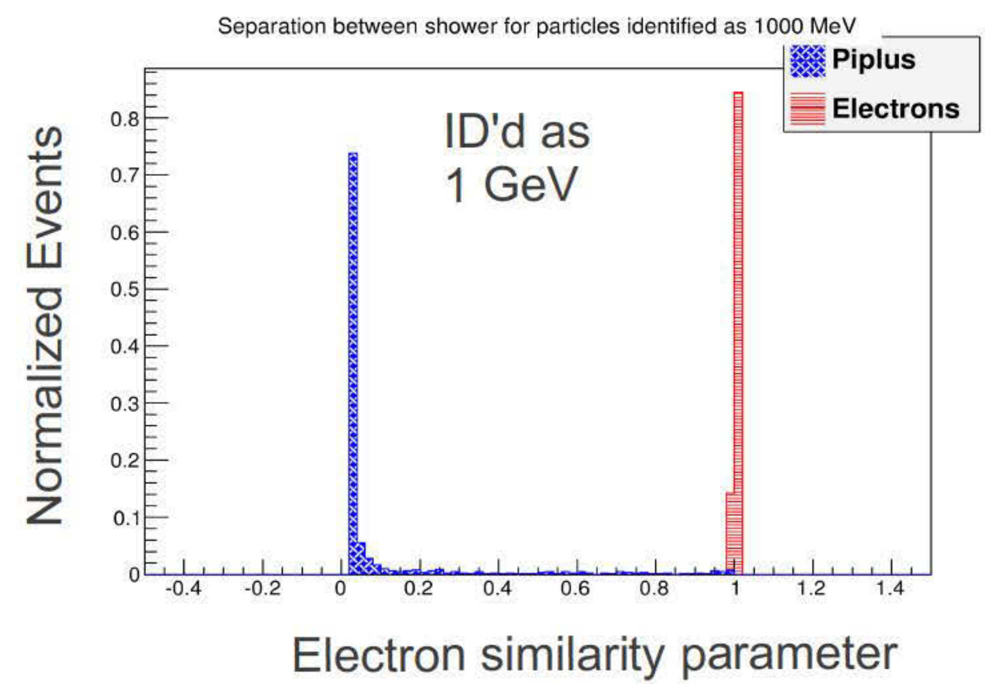
- The electrons were given an expected value of 1, and the pions were given an expected value of 0.

# Combined results



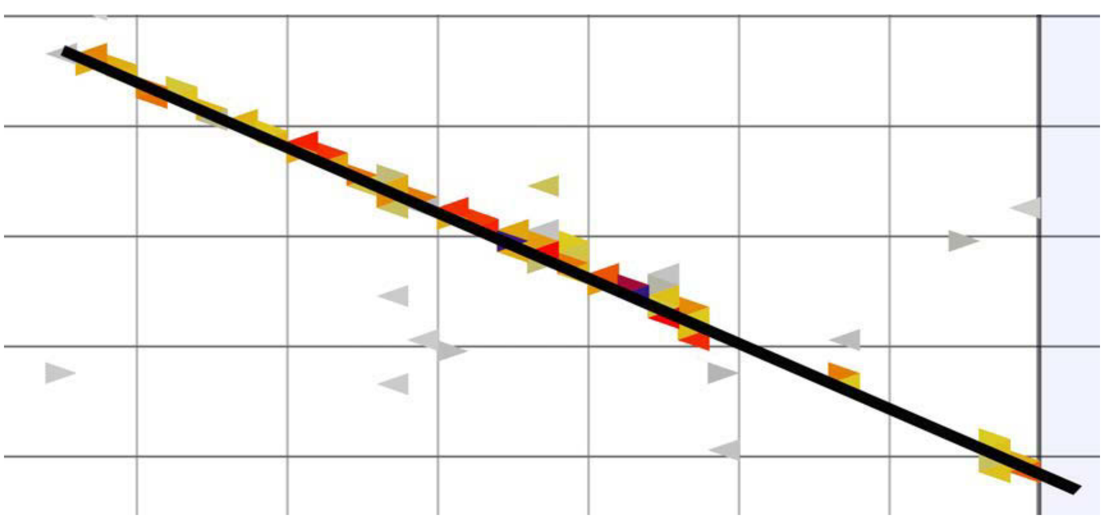
# Generalizing the results

- Heretofore, we have been considering a rather limited class of events in the detector:
  - Particles are generated parallel to the z axis
  - Particles start at the same point
  - No showers which reach the ecal are considered

- An attempt was made to apply the previously worked out discriminants to more general cases:
  - Particles generated at angles of up to 30 degrees were looked at
  - Particles starting at a wider range of positions in the tracker were examined, specifically starting from module 25 up to module 65
  - Showers which enter the ecal were included, necessitating the generation of templates in terms of radiation lengths rather than absolute length

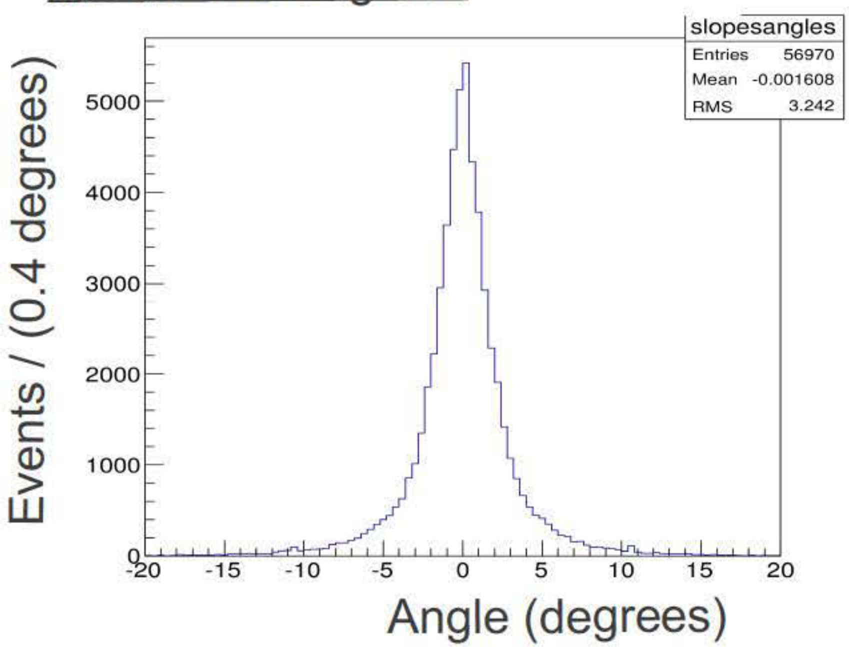
# Choosing a shower axis

- In order to make energy templates similar to those made for the simpler case, it is necessary to define an axis along which the energy deposition is examined
- It was decided to choose the axis in each view based on a least squares fit of the clusters, weighted by energy:



# Choosing a shower axis

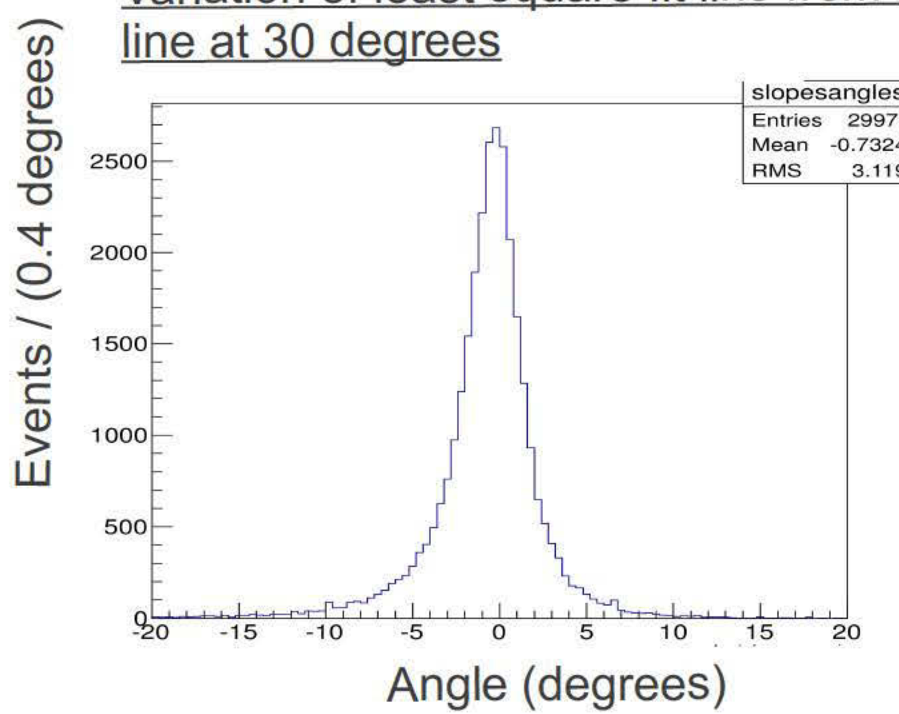
Variation of least square fit line from true line at zero degrees




- We can see that this is not an unreasonable assumption, as the weighted least squared fit produces an axis similar to the true axis for particles across a range of energies generated at zero degrees.

- For particles generated at thirty degrees, this remains a reasonably good approximation.

Variation of least square fit line from true line at 30 degrees



# Showers entering the ecal

- When shower enter the ecal, their energy profiles must be scaled in terms of the radiation length of the material through which they're passing
- As the ecal contains 2mm thick layers of lead between the polystyrene scintillators, the radiation length will be much shorter in the ecal
- The radiation lengths of the tracker and ecal were approximated by assuming that the tracker is made entirely of polystyrene, and the ecal made of 34mm of polystyrene and 4mm of lead per module. They were combined using the formula:

$$1/X_0 = \sum w_j / X_j$$

where $X_{lead}$ = 0.56 cm and $X_{scintillator}$ = 42.4 cm.

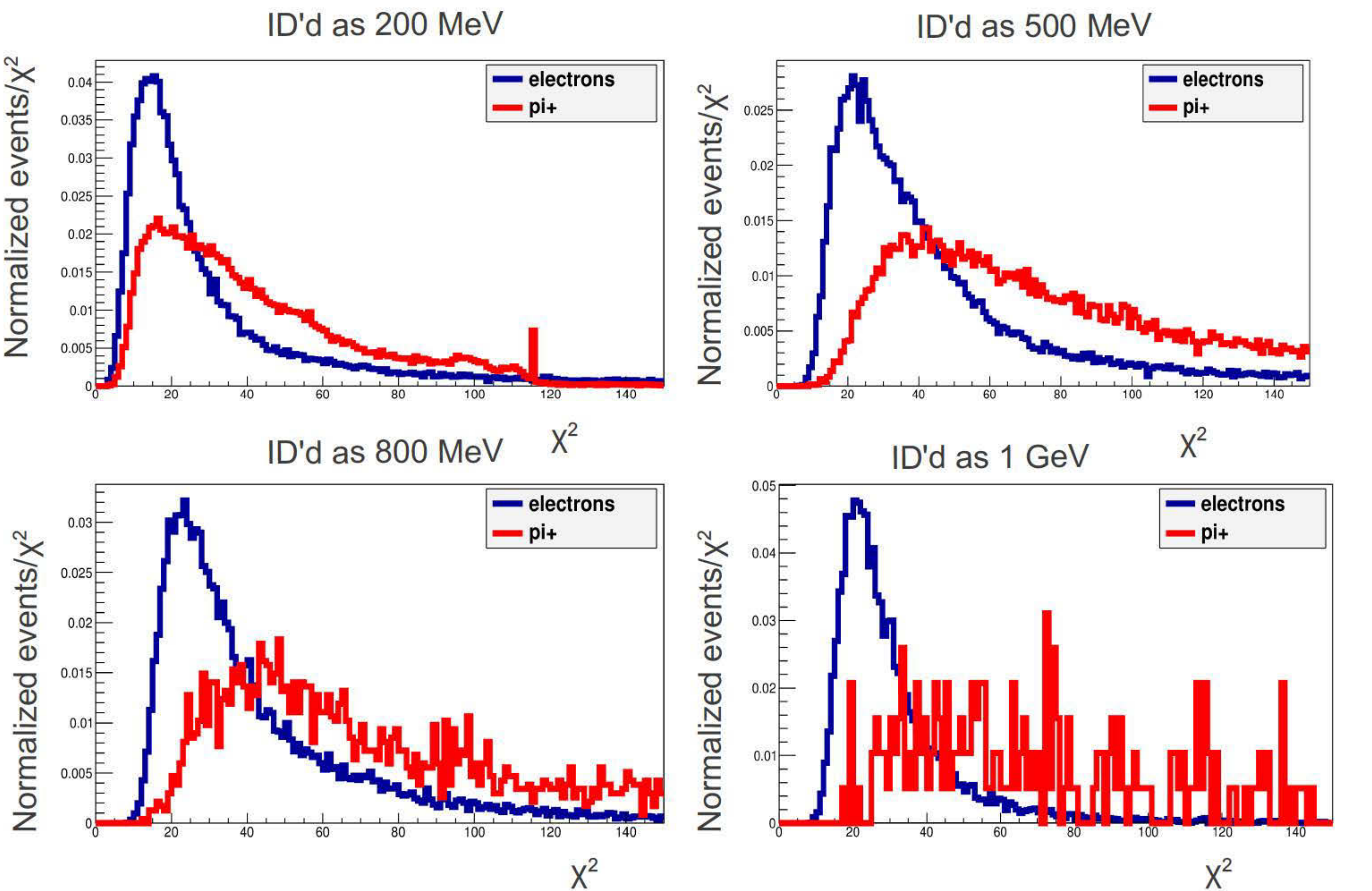
# Generalized shower parameters

- In this way, energy profiles can be determined for showers at all angles, and these can be compared to templates.
- With information about the shower axis, energy deposited near the start and end of the shower, and within our “cone” and “cylinder”, can be defined relative to the axis
- The energy for the first 20% of the shower will now be taken from a length which is scaled in terms of radiation lengths
- The energy at the end of the shower will now be taken from the last half of a radiation length.

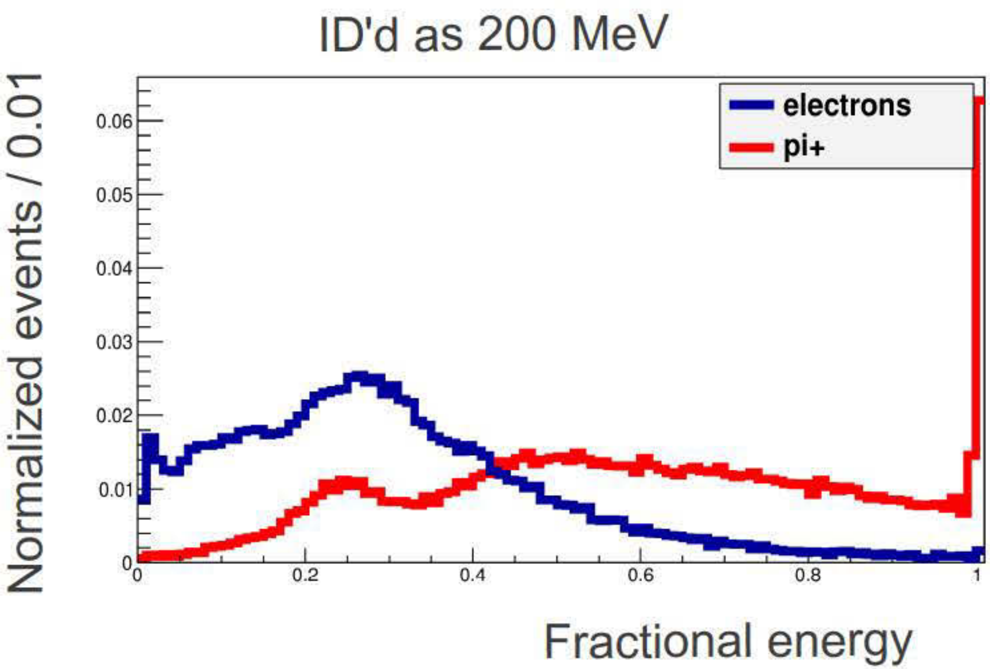
# Generalized shower parameters

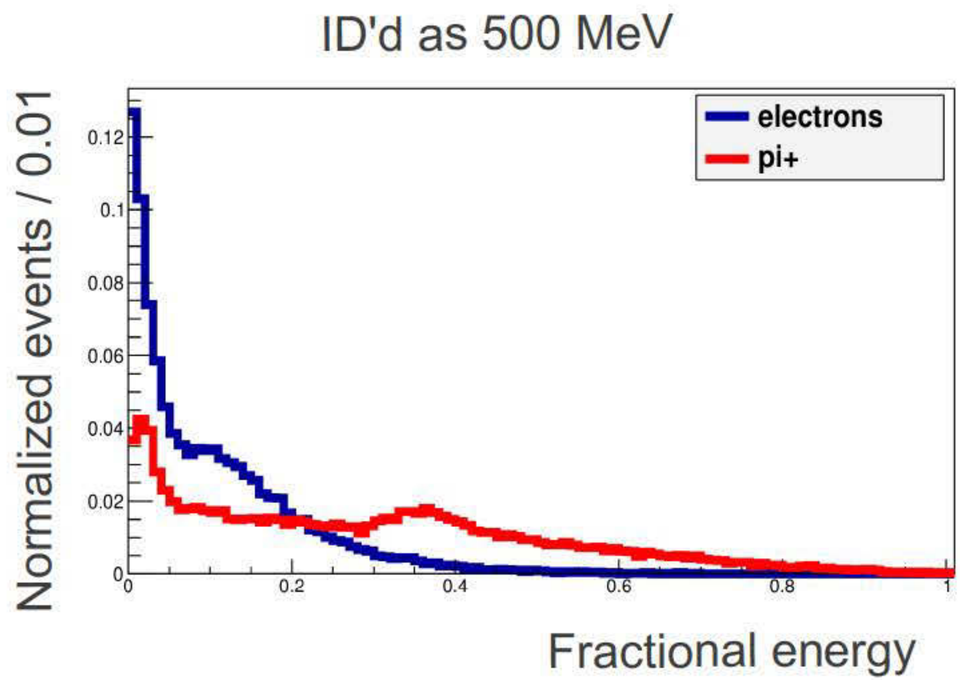
- The chi-squares will now be obtained by comparing to slightly more general templates
- These templates are obtained simply by varying the start position of the shower and scaling the length in terms of radiation lengths, to get a longer energy profile

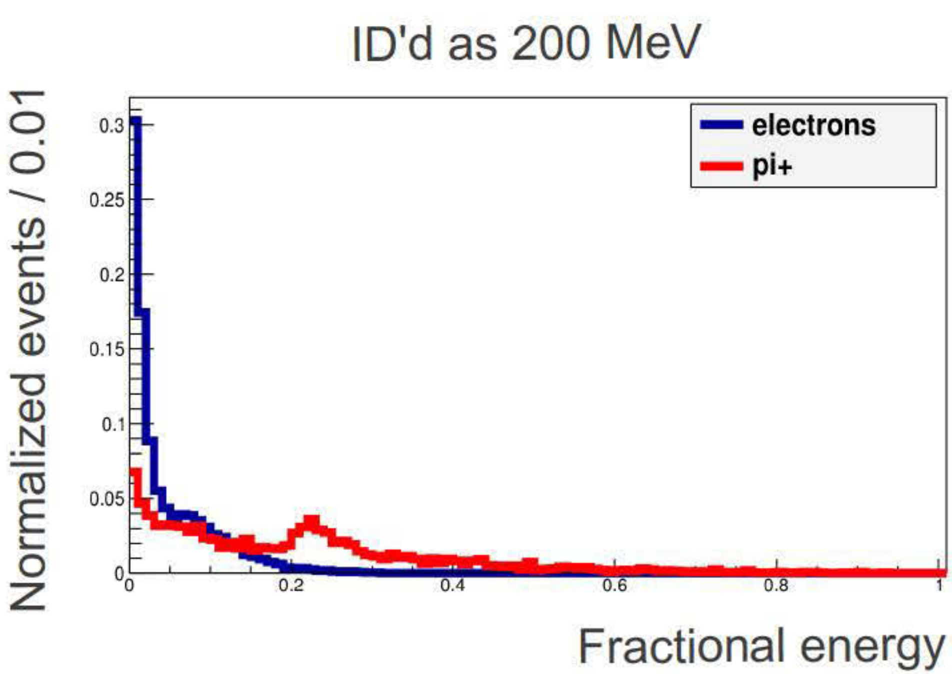
# Chi-squares compared to templates

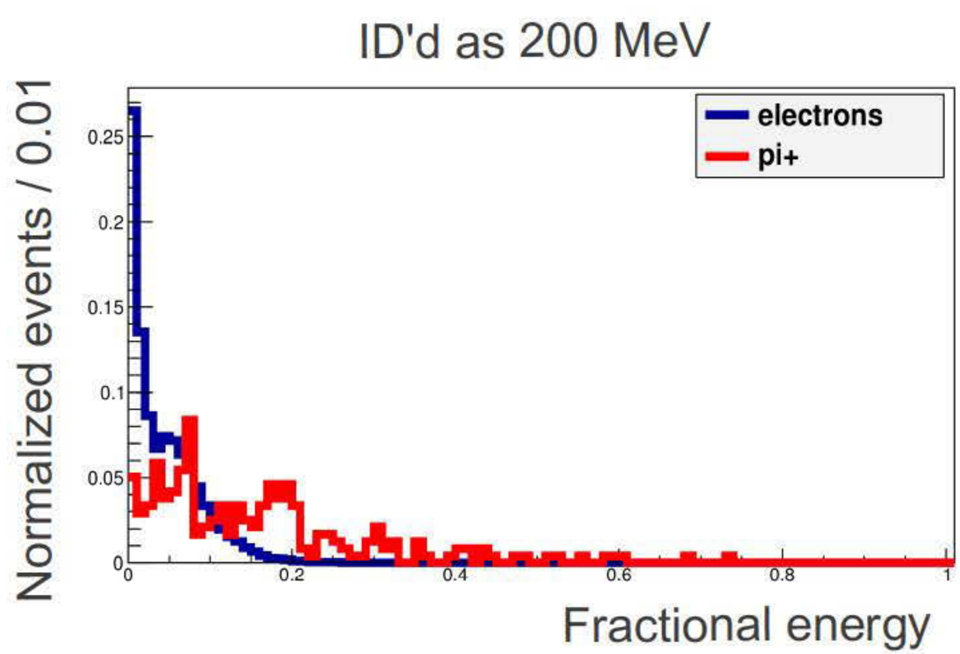


# Energy deposition in last half radiation length

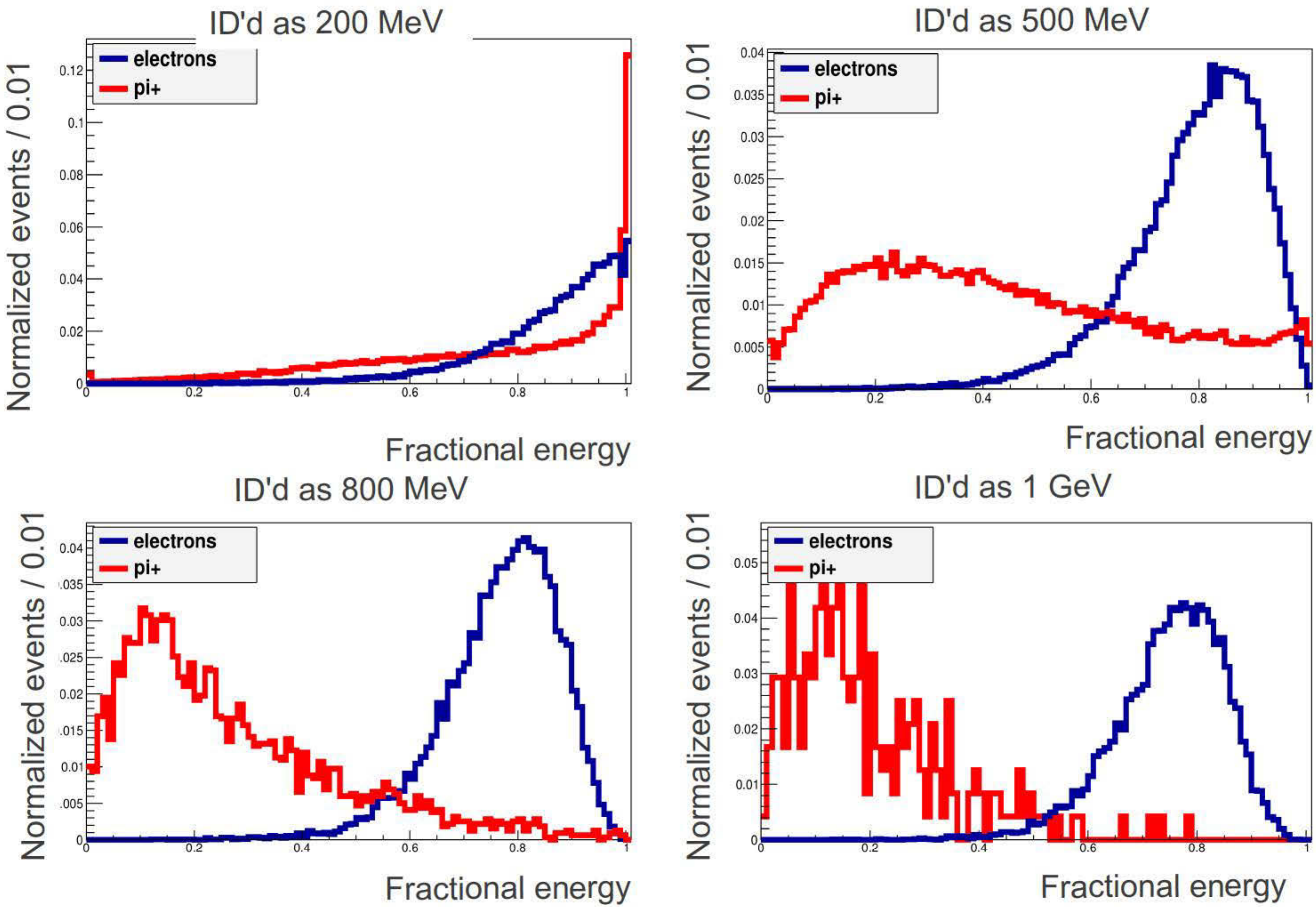


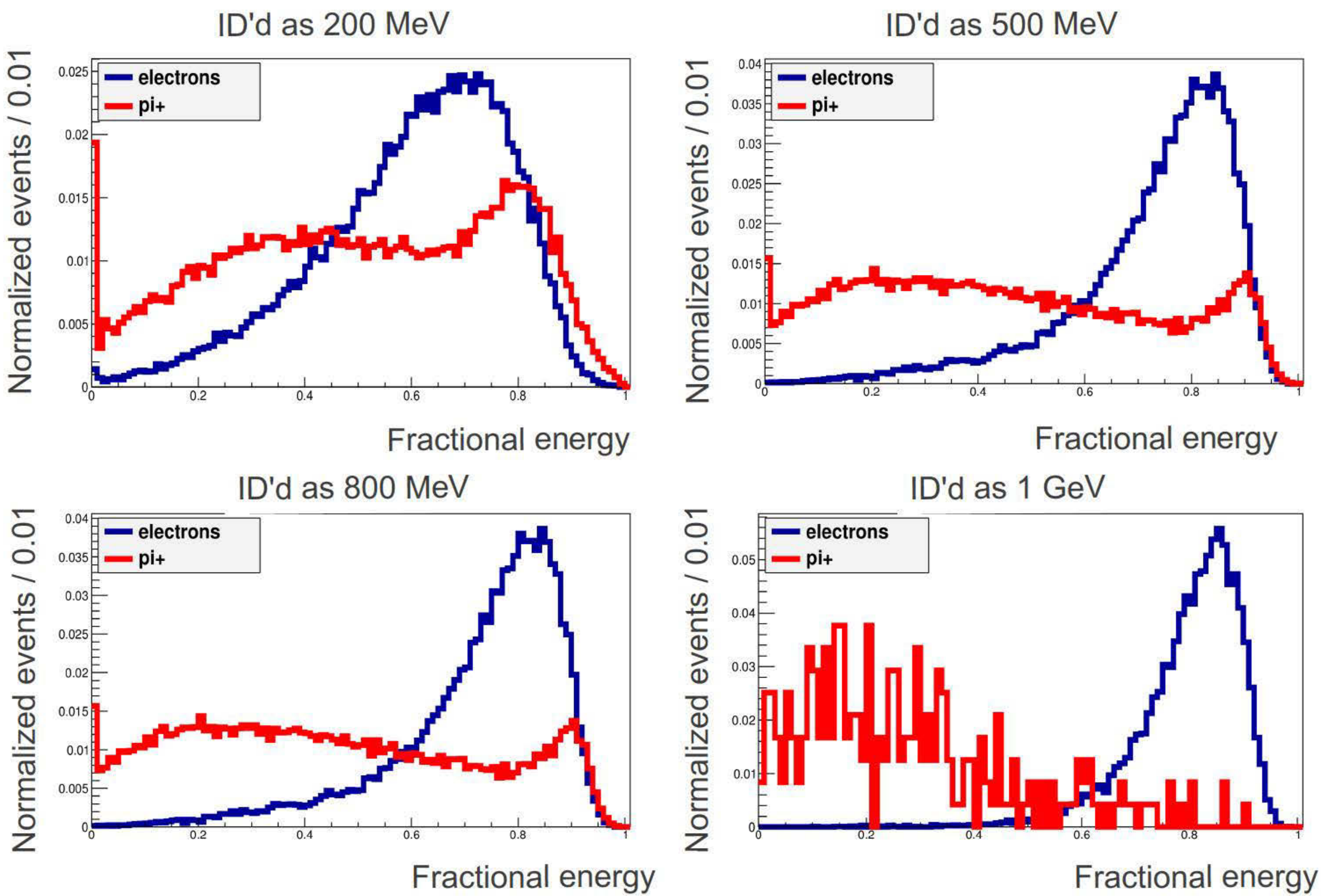



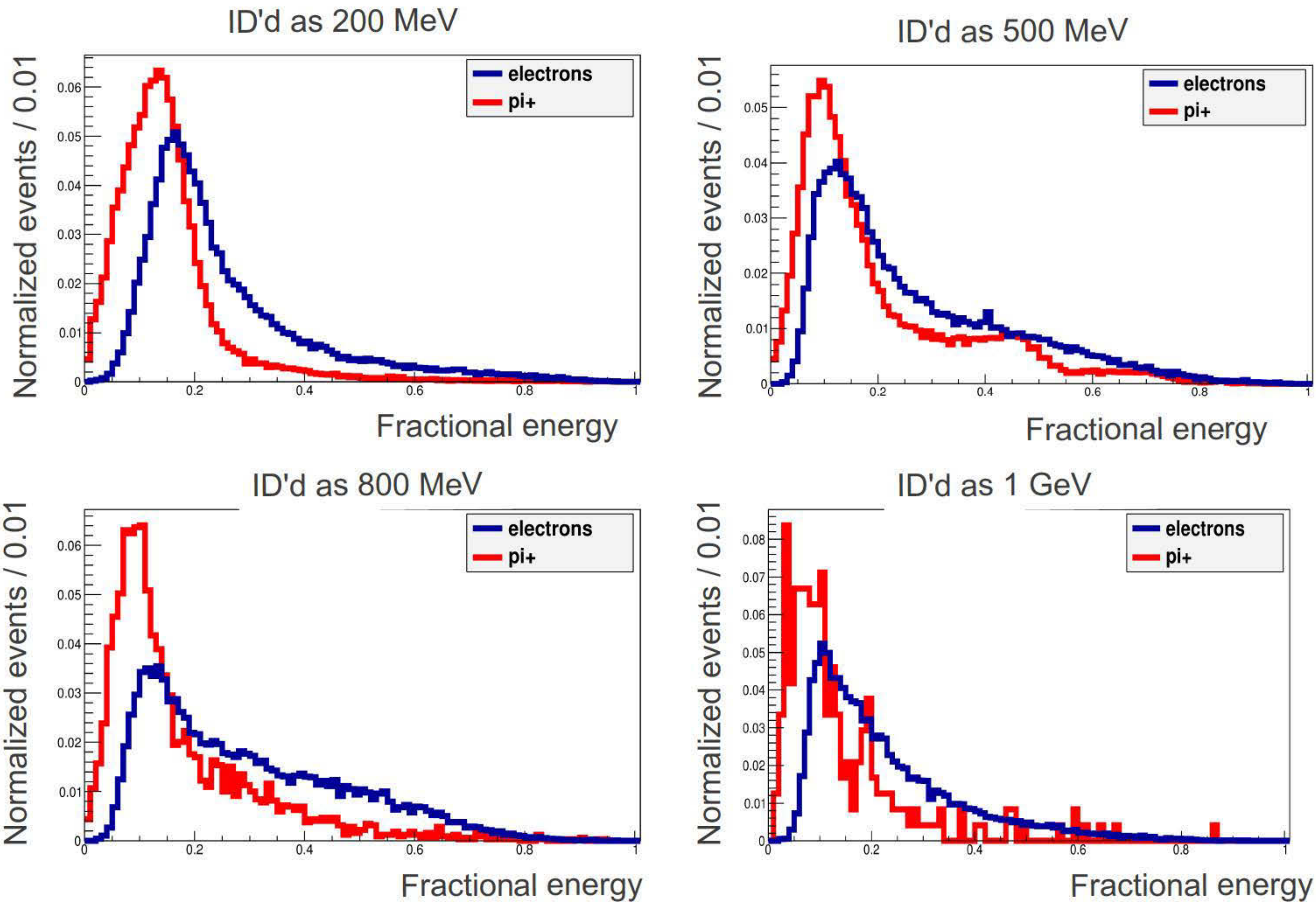
# Energy deposition within a “cylinder” of radius 20mm



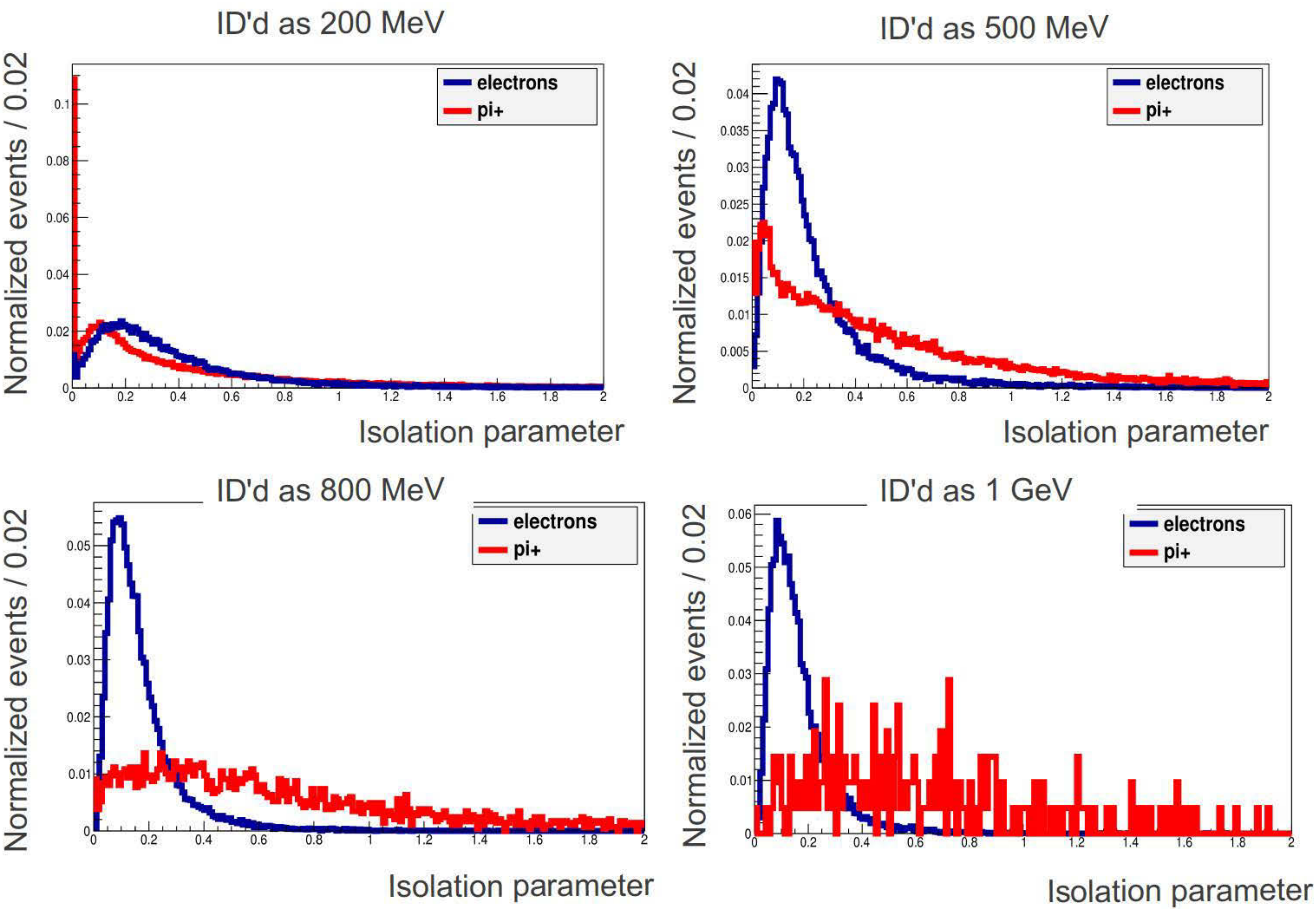
# Energy deposition within a “cone” of angle 0.03 radians



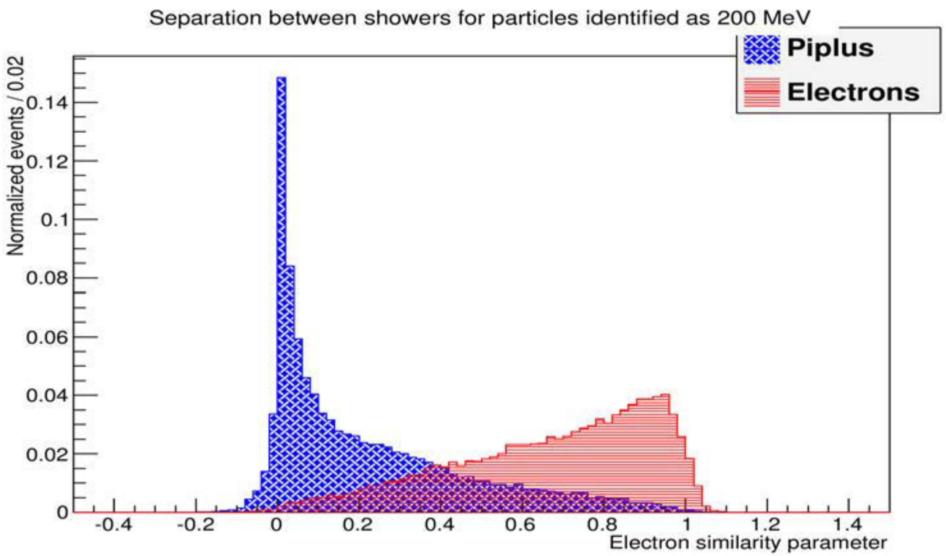
# Energy deposition within first 20% of scaled shower length

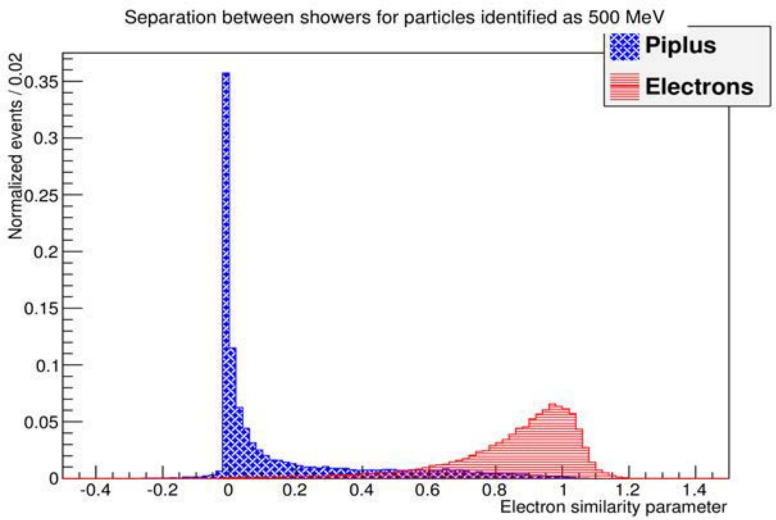


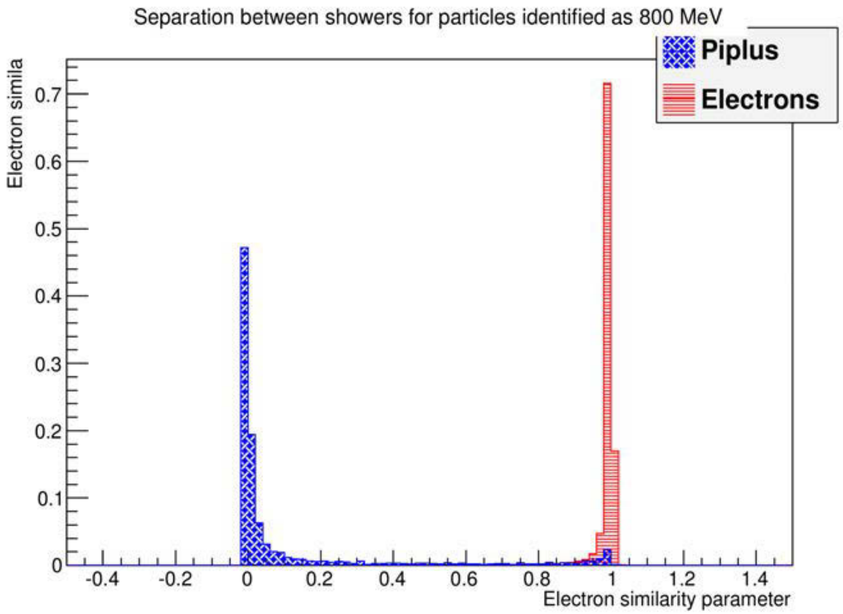
# Isolation parameter with α=0.03 radians

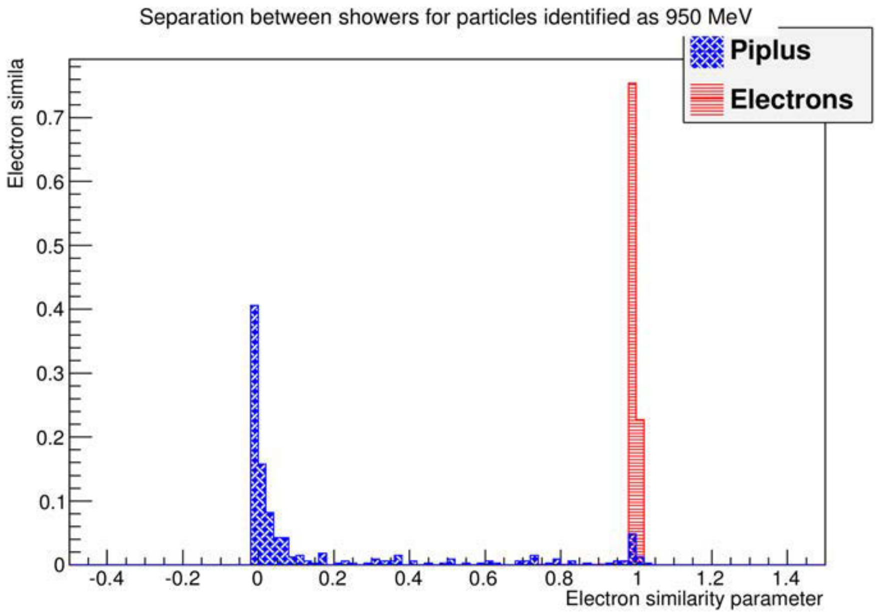


# Combined results



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